MASTER OF SCIENCE

Randomised cross-over trial assessing the impact of angle, area, distance, curvature, volume, spatial coordinates, and effect of eye exercises in surgical task performance 2D vs 3D laparoscopic vision

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Randomised cross-over trial assessing impact of angle, area, distance, curvature, volume, spatial coordinates and effect of eye exercises on surgical task performance: 2D vs 3D laparoscopic vision

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List of abbreviations

2D 2-Dimensional

3D 3-Dimensional

CSC Cuschieri Skills Centre

HD High Definition

HRA Human Reliability Analysis

GOALS Global Operative Assessments of Laparoscopic Surgery

SAGES Society of American Gastro-Intestinal Surgeons

VAS Visual Analogue Score

Sq Square

Cir Circle

Cr Creation test

Mr Measurement test

Cp Comparison test

MW- Maddox Wing

NOE Number of errors

NOM Number of movements

NOO Number of object

PP Pastpointing

TWO Touching wrong object

NR Not reaching the object

Dedications

To my lovely parents and sisters,

who have been always supportive and helpful.

To my late grandmother,

who had always gave me a special preference.

To my respected patients (alive and living),

who have taught, teaching and will always teach and inspire me.

Acknowledgements

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The hardworking lab colleagues Mr David Howie, Mr Alan Duncan, Mr Gordon Hogg who have been helpful in various technical and non-technical things.

And finally my respected participants in this experiments who have contributed their time and energy without any financial returns.

Declaration

I declare that the experiments described in this thesis were completed by me at Cuschieri Skills Centre of University of Dundee at Ninewell's Hospital and Medical School under the supervision of Mr Afshin Alijani. This thesis is composed by myself and has not been submitted previously for any higher degree. Ethical approval for this study was granted by the University of Dundee Research Ethics Committee.

Dr Gobinath Ramakrishnan

Statement from the Supervisor

This is to certify that Gobinath Ramakrishnan has fulfilled the relevant conditions of ordinances of the University of Dundee and he is qualified to submit the following thesis for the Degree of Master in Science by Research.

Mr Afshin Alijani

Publication and Presentation

PUBLICATIONS

- El Boghdady M, Ramakrishnan G, Tang B, Alijani A. A comparative study of generic visual components of two-dimensional versus three-dimensional laparoscopic images. World Journal of Surgery, Sept 2017.

- El Boghdady M, Ramakrishnan G, Tang B, Alijani A. A study of the visual symptoms in two-dimensional versus three-dimensional laparoscopy. American Journal of Surgery, Aug 2018.

POSTER PRESENTATIONS

- Michael El Boghdady, Gobinath Ramakrishnan, Benjie Tang, Afshin Alijani. A comparative study of six generic visual components of 2D vs 3D laparoscopic images.
  The Society of Academic and Research Surgery (SARS), The Royal College of Surgeons in Ireland, Dublin, 18th and 19th January 2017 (SARS, Patey Prize session)

- G Ramakrishnan, M El Boghdady, B Tang, IS Tait, A Alijani. The effect of change of angle, area, distance, volume, curvature and spatial coordinates on surgical task performance in 2D vs 3D laparoscopy. International Surgical Congress of The Association of Surgeons of Great Britain and Ireland (ASGBI), Belfast, 11th to 13th May 2016

- M El Boghdady, G Ramakrishnan, B Tang, IS Tait, A Alijani. Operator's visual symptoms in 2D versus 3D. International congress of the European Association for Endoscopic Surgery (E.A.E.S.), Amsterdam, 15th to 18th June 2016

Abstract

Background

There is a good body of evidence to suggest that 3 dimensional imaging improves surgical task performance during laparoscopic surgery. This improved performance in surgical task, however comes at a price of increased eye strain for a subgroup of surgeon. This often causes headache and even nausea. However to date, no study has been reported in explaining the underlying scientific reasons for the apparent improvement in 3D surgical task performance nor the causes for the eye strain and possible ways to minimize this squeal.

Objective

This study was aimed to investigate the effect of angle, area, distance, volume, curvature and spatial coordinates in 3D versus conventional 2D imaging in laparoscopic surgery. Furthermore, the rate of visual symptoms seen in 3D laparoscopic surgery and any possible intervention to alleviate this problem need to be addressed.

Hypothesis

The volume and spatial coordinates will be significantly affected in 3D imaging compared with other components of angle, area, distance and curvature. The 3D visual symptoms will be significantly influenced by introduction of simple eye exercises before the 3D task.

Study design

A prospective, cross-over and randomized study in a purpose built, state of the art laboratory setting based at the Cuschieri Skills Centre (CSC).

Methods and materials

A full research protocol was submitted for ethical approval. Consented students with no previous laparoscopic surgical experience were chosen among medical students at the University of Dundee. The standardized surgical tasks were set up in a purpose built body trainer with laparoscopic ports inserted for the introduction

of either a thirty degree 2D or 3D camera scope. 24 students were recruited for the study.

The students were required to undergo a visual acuity test (Snellen chart) and eye deviation test (with Maddox Wing). They were then asked to grade on visual analogue scale symptoms before and after the 2D and 3D laparoscopic tasks. Those who underwent 3D laparoscopic tasks were randomized into two group; one arm, who received eye exercises and the other arm without any eye exercises before the laparoscopic 3D tasks. A battery of specific isolated laparoscopic tasks was developed to test their ability to detect changes in 2D and 3D environments separately. The six endpoints were the accuracy in detecting changes in the following components: 1) angle, 2) area, 3) distance, 4) volume 5) curvature and 6) spatial coordinates. All the components except the spatial coordinates were assessed in three different methods: creation, measurement and comparison. The results were analysed with paired and independent t test using IBM SPSS version 22.0. Spatial coordinate tests were video recorded and subjected for Human Reliability Analysis (HRA).

Results

There was no statistical difference in angle, distance and curvature in 2D versus 3D imaging but there was a statistical difference for square measurement at 7cm, volume measurement at 3ml and volume comparisons which showed significance in 3D imaging. The most accurate level for distance creation is 2cm and for distance measurement is 4cm and for circle measurement is 4cm. For angle, the most accurate degree for creation is 5 and for measurement is 35 in both imaging. And for volume assessment, 3ml was noted to be most accurate volume for both volume creation and measurement in 2D and 3D imaging. The spatial coordinates produced statistical significance results in 3D imaging and we could safely conclude that spatial coordinates was the pivotal for the enhanced 3D imaging. Error probability calculation revealed that a 10 percent higher probability of committing errors in 2D compared to 3D. For type of errors, pastpointing and touching wrong objects were higher in 2D and statistically significant ($p=0.001$, $p=0.038$). For visual symptoms, eye strain was significant in 2D with $p= 0.022$ and difficulty in refocusing from one distance to another was significant in 3D with $p =0.035$. For visual symptom between the 2D and 3D imaging, difficulty in refocusing from one distance to another was significant in 3D ($p=0.027$). Performing simple eye exercises before 3D imaging had no effect on relieving visual symptoms.

Conclusion

Spatial coordinates was the underlying reason for the better task performance in 3D surgical imaging. Eye strain was prominent in 2D imaging and difficulty in refocusing from one distance to another was annoying in 3D. Besides, eye exercises before the 3D laparoscopic tasks as a possible solution for 3D visual symptoms did not bring any significant results.

CHAPTER 1

Chapter 1 Introduction

1.0 Problem statement

Laparoscopic surgery is the standard of care for most of the abdominal diseases now. Moreover, the surgical curriculum has been revised to accommodate more training on laparoscopic skills. Despite the great benefits of the conventional 2D laparoscopic system, there are setbacks associated with 2D system especially the lack of depth perception and tactile feedback. The introduction of the 3D laparoscopy system in the late 1990s managed to address some of the problems faced by the 2D laparoscopy system. The evidence is robust that 3D offers better surgical task performance, but there is no study on the underlying reason for this apparent task performance enhancement or the adverse effects associated with 3D laparoscopy.

1.1 Background

Field of laparoscopic surgery has advanced tremendously in recent years. The studies so far have shown that 3D laparoscopy had superior task performance, but there are adverse effects associated with 3D system such as eye strain and headache. By and large, these studies on 3D imaging measured the task performance based on the surgical errors and performance time.

1.2 Research gap

So far, the literature review showed that task performance and surgical errors were assessed by utilizing a surgical task which itself is an accumulation of multiple small steps (components). For example, the Fundamentals of Laparoscopic Modules which is a core laparoscopic surgical training program in USA composed of five main tasks. These tasks are peg transfer, precision cutting, ligating loop, extra-corporeal knotting and intra-corporeal knotting. The execution of this task which may appear straightforward but it really consists of multiple small steps or interplay of various dimensions such as distance, force and time. Nevertheless, there were no papers to study the effect of basic dimension especially distance as an independent factor in surgical task performance in 2D and 3D laparoscopy.

1.3 Justification of the study

Learning of laparoscopic skills is a time consuming process and involves hand eye coordination, manual dexterity and visual spatial coordination. The transition from open surgery to laparoscopy surgery needs a different mindset. For instance, when operate in a 2D view, the surgeon's mind has to reorganize the images from 2D form to 3D in his brain. This is aggravated by narrow working space, magnification, lack of depth perception and pressure of acquiring new skills. The transition from 2D laparoscopy to 3D laparoscopy needs the mind to adjust the artificial 3D to self-constructed 3D view at the expense of visual strains. Thus we hope that by studying the underlying reasons for improved task performance in 3D versus 2D, we are able to shed some light on the fundamentals of laparoscopy and help in the training of laparoscopy.

1.4 Aim of the research and method

Once we analyze a surgical task, we are able to derive the basic components which are the tenets for the task execution. These components are distance, force and time. The notion of distance can be expanded to area, volume, curvature and angle. The measurement of force is complex as force is the derivative of mass and acceleration. The force in the surgical field can be generally divided into squeeze or push/pull factor. Finally, time can be perceived as a passage of the time in task performance or duration spent on performing the task.

The interplay of the basic components of distance, force and time creates a surgical task. For example, in the laparoscopic cholecystectomy, the Calot's triangle dissection needs a surgeon to be able to estimate or measure the distance of the cystic structures from the common bile duct or the common hepatic duct; able to estimate the force for the clipping of cystic structures or fundal retraction and finally able to complete the dissection within the appropriate duration.

For this study, medical students from School of Medicine, University of Dundee were invited to participate in the experiment at Cuschieri Skills Centre, Ninewell's Hospital. We created a battery of test which assessed the angle, area, distance, curvature and volume in isolation and independent to others. The tasks for each component were divided according to the method of assessment: creation, comparison and measurement. All the tests were performed in 2D and 3D environment. The spatial coordinate test which assessed the spatial coordinates component was video recorded for Human Reliability Analysis.

1.5 Hypothesis

The following hypothesis have been tested through this research:

1. The volume and spatial coordinates will be significantly affected in 3D imaging compared with other components of angle, area, distance and curvature.
2. The 3D visual symptoms will be significantly influenced by introduction of simple eye exercises before the 3D task.

CHAPTER 2

Chapter 2 Literature Review

2.0 2D vs 3D Laparoscopy

One of the greatest achievement in the medical field in the 20th century was the introduction of first fiber-optic lens system by Harold Hopkins and Narinder Kapany from Imperial College London in 1950 (Hopkins , Kapany 1954) (Figure 1, Figure 2). This fiber-optic technology spurred the interest and research in minimal access surgery. Hopkins patented the product in 1959 and he partnered up with Karl Storz(instrumental engineer) in 1967. Karl Storz then refined the technology and expanded its usage (Berci and Cuschieri 1996). Despite this amazing discovery, it took many years before the first laparoscopic cholecystectomy surgery which was performed by Dr Erich Muhe, the German surgeon in 1985. Early 1990s showed more laparoscopic surgical attempts throughout Europe in cholecystectomy and other procedures (Reynolds 2001). In 1991, Prof Alfred Cuschieri had forecasted that 70% of the surgical procedures would be done via key hole method before the end of the 20th century (Cuschieri 1991). The practicing surgeons now would not agree more with Prof Cuschieri’s opinion decades ago.

Figure 1: Harold Hopkins

Figure 2: Narindar Kapany

The shortcomings of 2D laparoscopy opened up opportunity for new technologies, notably 3D laparoscopy. The initial known report of 3D endoscopic system was by Becker in Journal of Endoscopy Surgery and Allied Technology in 1993 and he reported that 3D system was able to facilitate complex surgical procedures and envisaged its great future potential(Becker 1993). Since then, there are many papers which have been published on 3D and 2D laparoscopy.

Hanna and colleagues published a seminal paper in Lancet in 1998 and studied the advantage of 2D vs 3D system in laparoscopic cholecystectomy and found out that there was no difference between these two systems. They found out that 3D system was associated with annoying eye symptoms and facial discomfort(Hanna, Shimi, and Cuschieri 1998).

Hanna and his group evaluated 2D and 3D imaging in 10 experienced surgeons performing enterotomy on porcine models. The study showed no significant advantage of the 3D system in terms of execution time, leakage pressure, suture placement and depth perception but more visual strain symptoms in the 3D arm(Hanna, Cuschieri 2000).

Another paper in Journal of Surgical Endoscopy reported that second generation 3D system significantly improved laparoscopic precision of novice and experienced surgeons, without the side effects reported from the previous systems(Taffinder 1999). Precision in this study was assessed with Imperial College Surgical Assessment Device (ICSAD) which generated an objective score of the performance by analyzing the movements of the surgical instruments.

Study by Falk et al (2001) stated that trained as well as novice surgeons performed well with 3D training model in comparison to 2D training model. This was further supported by other study which found that the surgical task efficiency was remarkable in both novice and experienced surgeons in 3D laparoscopic system compared with 2D (Storz et al. 2012).

Another study by Smith, Day A group found that passive polarizing stereoscopic displays in 3D significantly improved surgeon performance, which was assessed by doing four surgical skills(Smith 2012). Honeck et al (2012) showed three-dimensional laparoscopic imaging improved surgical performance on standardized ex-vivo laparoscopic tasks. The results showed a significant difference in 3D system for the amount of missed grasps in the experts as well as the novice group. Bilgen et al (2013) found out in April 2013 that 3D system reduced performance time in laparoscopic cholecystectomy.

Wagner et al (2012) reported that 3D system enhanced task performance, independence of surgical method (open, laparoscopy and robotic). They demonstrated that performance speed can be raised by 60-70% with use of 3D imaging system. Indian gynecologists published their experience of minimally invasive surgery in 3D imaging and found that the tactile feedback was retained and the precision, accuracy and depth perception were remarkable. The time taken for the surgery as well as the morcellation of organ was less than the 2D laparoscopy system (Sinha, Rakesh 2013).

Another group demonstrated that 3D laparoscopy reduced the operating time in laparoscopic liver resection compared with high definition 2D imaging (Velayutham et al. 2015).

Lusch et al (2014) showed that 3D laparoscopic camera equipment brought out a significant improvement in depth perception, spatial location, and precision of surgical performance compared with the conventional 2D camera equipment. Another study showed that the new 3D imaging system increased the accuracy of laparoscopy performance, with greater depth perception and only minimal dizziness(Kong et al. 2010).

There is conflicting evidence about the benefits of stereoscopic surgery. Herron et al (1999) assessed 50 laparoscopic novices performing specific laparoscopic dexterity drills using four different displays: standard 2D, 3D monitor, 2D and 3D head mounted displays. The reduction of errors and performance time in 3D imaging were not significant. They concluded that improvement in 3D display resolution technology may improve the performance time. Similarly, Mueller et al (1999) compared conventional laparoscopy with 3D laparoscopy in 20 inexperienced and 10 experienced surgeons and found no significant advantages of the 3D system. 3D systems were also associated with a higher incidence of headaches, fatigue and required longer familiarization time.

As some papers triumphed the superiority of 3D laparoscopy, there were other studies which had failed to detect the difference of task performance between 2D and 3D system. There were many reasons for this discrepancy. The surgical task performance depended on task difficulty and complexity, in some studies the task was easy, straightforward and in others, the task was challenging. The recruitment of subjects with different level of expertise was also another reason. Besides that, some of the earlier studies used first generation 3D laparoscopy system with lower resolution, which affected the depth perception, visual cues and may have influenced the end results.

The interest in 3D imaging among the general surgeons is still low compared with urologists. Urologic field had pioneered the utilization of robotic surgery with the incorporation of the benefits of 3D imaging. This is the main reason why the 3D surgical imaging garnered more attention among the urologists instead of general surgeons. But the skepticism arises when the real benefit of the performance or other form of evidence outcome is difficult to be discerned as people start to contemplate what makes the robotic surgery superior, is it because of robotics technology with more precision or is it because of more superior 3D surgical imaging? There was a study by Japanese authors in Journal of Robotic surgery in which they assessed the robotic dexterity in 2D and 3D. They concluded that robotic suturing in 3D was faster than in 2D imaging(Ishikawa et al. 2007). And another study by Badani et al (2005) also showed the advantage of robotic suturing in 3D. Nevertheless, the evidence is scarce and it is not the intention to dwell on robotic surgery in this thesis.

The systemic review in April 2015 from Danish colleagues showed that 3D laparoscopy improved speed and reduced performance errors significantly compared with 2D laparoscopy. Their review assessed four salient aspects of laparoscopic surgery; performance time, precision or errors, side effects and cognitive workload. They found out that only three RCT have been done in clinical settings compared with 28 RCT in simulated settings (Table 1). The scarcity of clinical settings papers showed that 3D imaging was not popular among surgeons. Some of these papers failed to explain how the randomization was carried out and the presence of heterogeneity made the process of meta-analysis impossible

(Sørensen et al. 2015). The authors suggested that more clinical based 3D surgical procedures needed to be done to assess the real impact of 3D imaging.

Study	Cohort size	Procedure	Results	Conclusion
Sahu , Reddy (2014)	3D: 13 patients 2D: 40 patients	General surgery , ovarian cystectomy	3D surgery showed reduced operating time, and better operative parameters, hand eye coordination, depth perception and intra-corporeal knotting. Eyestrain present in 3D.	3D laparoscopy is better with reduced operating time and improved operative parameters except for eye strain.
Kaufman et al (2007)	3D: 44 patients 2D: 44 patients	Gynaecology surgery	3D surgery showed reduced operating time, better depth perception, confidence, efficiency, anatomical understanding	3D decreased performance time for both novices and experienced surgeons. 3D was associated with increased surgeon confidence and no visual symptoms.

			and no side effects.	
Hanna, Shimi, and Cuschieri (1998)	3D: 30 patients 2D: 30 patients	Lap cholecystectomy	3D surgery showed no change in operating time or errors, increased depth perception but increased visual strain and discomfort	3D shows no advantage over 2D systems in laparoscopic cholecystectomy. Annoying eyestrain present in 3D.

Table 1: Summary of RCT in clinical settings for 2D vs 3D laparoscopy

2.0.1 Laparoscopic skills acquisition in 2D vs 3D

The surgical skills training is considered very steep and time consuming as a trainee needs to learn both the open surgical skills and minimal access surgery before performing surgeries in the operating theater. The emphasis that is placed on laparoscopic training in the surgical education is not standardized and differs as there are many reason for this: the availability of surgical simulators, skilled trainers, crowded surgical curriculum and work hours restrictions. There are many papers which looked at the role of 3D imaging in laparoscopic skills acquisition among the surgical trainees.

A group from Texas studied medical students (novice) and surgical residents (experienced) in which they were asked to complete laparoscopic tasks in 2D or 3D imaging and were retested after three months in the opposing imaging system. They found that teaching laparoscopic skills in 3D gave better advantages to inexperienced individuals compared with 2D imaging (Votanopoulos et al. 2008). Alaraimi and group published a randomised prospective study comparing acquisition of laparoscopic skills in 3D vs 2D in 2014. They found that stereoscopic vision improved accuracy in laparoscopic skills for novices, which was manifested in reduced numbers of repetitions and errors in the tasks (Alaraimi et al. 2014).

Tanagho and colleagues applied the selected skills of the validated Fundamentals of Laparoscopic Skills in 2D and 3D environment and found that 3D vision improved laparoscopic proficiency based on objective measures (completion time and errors committed) and subjective measures (questionnaires).

2.1 Adverse effects of 3D laparoscopy

Kong et al (2010) reported that 3D laparoscopy caused nausea, dizziness and eye fatigue. This similar findings were reported by Chan et al (1997) and (Hanna, Shimi, and Cuschieri in 1998). Alaraimi et al (2014) showed that 3D imaging caused tiredness and there was no significant eye strain, nausea or dizziness. They postulated that tiredness could be due to the stress of acquiring new skills rather than the technology itself. A latest study by Chinese authors from Anhui Medical University in Journal of Endourology in Feb 2015 revealed that 3D surgical imaging caused visual fatigues from a subjective assessment (from the questionnaire) but the there was no statistical significance in objective measurement of visual fatigue. They measured visual fatigue using various devices in collaboration with ophthalmologists. The paper concluded that the surgeons were able to tolerate the moderate visual fatigue with no effect on task performance(Zhou et al. 2015). Despite extensive findings on visual symptoms associated with 3D imaging, there was no available literature on any possible solution to alleviate the visual symptoms. Our study was designed to analyse the effect of eye exercises in 3D imaging and to assess any significant benefit in exercising eye muscles. Eye exercise is one of the therapy for many visual problems such as myopia and visual-motor disturbances. Apart from that, eye exercises is compulsory among Chinese pupils and they need to exercise their eyes twice in a day to relieve ocular fatigue and reduce myopia(Lin et al. 2013). Thus, it would be interesting to explore the applicability of eye exercises in minimal access surgery.

2.2 Aptitude and psychomotor

One of the widely discussed concept is the aptitude and psychomotor ability among the surgeons and its correlation with task performance. Aptitude is defined as a natural ability to do something. The concept of aptitude has grown tremendously in recent years and has expanded in many disciplines. Psychomotor is defined as a relationship between the cognitive function (psycho) and physical movement (motor). Psychomotor ability is demonstrated by physical skills such as movement, coordination, manipulation, dexterity, strength and speed. The psychomotor ability also includes ability to apply fine motor skills such as use of precision instruments. When learning psychomotor skills, individuals progress through three essential stages: cognitive, associative and autonomic stage. The cognitive stage is characterized by awkward, slow and choppy movement that learners try to think and control each movement before attempting it. In the associative stage, the learner spends less time to think about the each movement and in the final stage, the learner is able to refine his movement with practice, without the need of thinking (*Psychomotor and Learning* 1986).

In the surgical field, aptitude test was first introduced by KS Graham in 1991(Graham 1991). He projected that there was a big advantage in the aptitude testing in surgery. Since then, there were many papers which had been published in surgical aptitude. There are some innate abilities that form the core of laparoscopic surgery. These are the hand eye coordination, manual dexterity, visuospatial ability and others.

CJ Harris et al (1994) published in British Journal surgery about psychomotor skills of surgical trainees compared with other medical specialists. They looked at manual dexterity, hand eye coordination and visuospatial ability in various tests. They found that surgical trainees performed significantly more quickly in spiral maze test (hand eye coordination) but made more errors compared with other trainees, but there was no difference in visual spatial ability and manual dexterity.

Another paper analysed the psychomotor abilities of the master surgeons in manual dexterity, hand eye coordination and visuospatial ability in their surgical performance. They found that master surgeons performed well in manual dexterity and hand eye coordination compared with the average norm (Nader K. et al. 2001). Park Hyunmi et al (2011) looked at measuring surgical aptitude test in open, laparoscopic, endoscopic and virtual reality simulator performance. They used computer based FAT (Flying Aptitude Test) and correlated the surgical performance to FAT. The FAT measures the following parameters in six domains: verbal reasoning, numerical reasoning, spatial reasoning, attentive capability, work rate and psychomotor coordination. They concluded that there was a statistically significant correlation between the FAT and all three modalities of surgery; open, laparoscopic and endoscopic. They summarized that this test could be used as an adjunct to select surgical trainees who were able to complete the surgical training and practice independent, safe surgery.

2.2.1 Spatial ability

Spatial ability is defined as the skills of creating, transforming, representing and recalling symbolic, non-linguistic information (Alias, Maizam 2002). Currently, there are three categories that influence spatial ability: spatial orientation, spatial visualization and spatial cognition. Spatial orientation is defined as the comprehension of arrangement of elements within a visual stimulus and the capacity to remain unconfused by the changing orientation or coordinates in which the spatial orientation may be presented (McGee 1979). Spatial visualization is defined as the ability to mentally rotate, manipulate, twist or invert a pictorially presented stimulus. In other words, this is defined as a capacity to manipulate an object through imagination and build a virtual representation of the same object from a different angle. Spatial cognition is the fundamental cognitive process that enables an individual to develop spatial abilities (Strong, S 2002).

Mental rotation is one of the most researched components in spatial visualization. It is described as the imagined version of a physical rotation whereby a given object is translated about an imagined pole in either 2 or 3 dimensional space (Ark, Road, and Jose 2002). Shepard and Metzler (1971) described the principle of mental rotation first, demonstrated that matching drawings of rotated 3D objects took increasingly more time as the angular difference increased, especially in the depth plane. Mental rotation has been described by many as the gold standard for measuring spatial cognition in humans (Driscoll et al. 2005) and is believed to be a vital skill in completing both simple and complex tasks.

2.3 Measurement of distance in surgery

Distance plays an important factor in the surgical field. A surgeon should be competent in measuring and estimating distance to enhance task performance. This quality is further compromised in 2D laparoscopic system with the advent of magnification, resolution and depth perception. For 3D laparoscopic system, the concept of distance needs different form of understanding and cognitive function.

The ability to measure distance is essential as a surgeon has to estimate the distance of the crucial structures in the working area. For example, the widespread practice of mesh based repair in the groin, incisional and ventral hernia underscores the importance of distance. Apart from that, measurement of the small bowel length for the alimentary and pancreatic- biliary limb in bariatric surgery needs best estimation of the distance.

In the laparoscopic world, the notion distance is equivalent to depth perception. Depth perception is defined as the ability to judge the distance of objects and the spatial relationship of objects at different distances or coordinates.

These visual cues are important for depth perception and can be broadly divided into the following four categories: (Nicolaou Marios 2006)

- Monocular cues (require only one eye)
- Cues arising from motion parallax
- Binocular cues (require two eyes)
- Proprioceptive feedback

2.3.1 Monocular cues

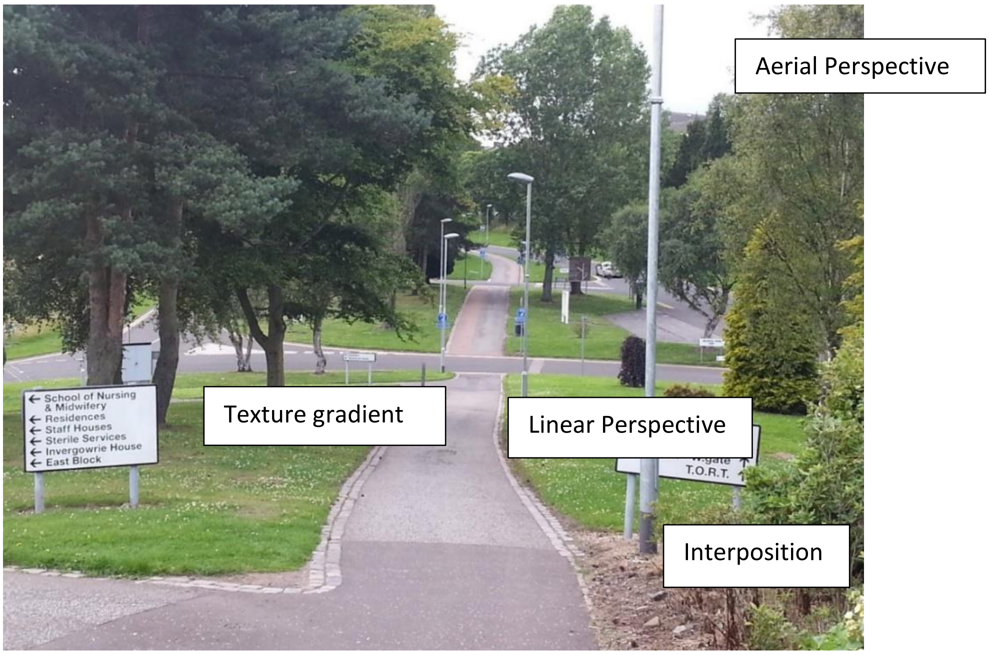


Figure 3: Monoocular cues in the pictorial form

These are depth cues that only need one eye (Figure 3):
Relative size: the projected image of an object onto the retina diminishes in size as the object is moving away from the observer.

Interposition: overlapping or occlusion occurs when an object obscures part of another object which the brain interprets as being further away.

Familiar size: the distance of a known object from the observer can be gauged by comparing the apparent size to the expected one.

Texture gradient: the texture of a surface becomes smoother and finer as it goes into the distance.

Linear perspective: objects that are further away subtend a smaller angle and parallel lines are perceived converging at one point in the distance.

Aerial perspective: objects at a greater distance appear to have different colour (e.g. the hazy bluish tint of distant mountains).

Shadow: this clue can provide useful information about an object such as dimension, orientation and depth. The principle relies on the fact that objects usually do not allow light to pass through and therefore cast a shadow. The direction and magnitude of the shadow depend on the intensity, angle and number of light sources available.

Relative brightness: brighter objects appear nearer.

2.3.2 Motion parallax

This monocular cue relies on the apparent different speeds of objects located at different distances from an observer whilst the observer is in motion. Nearer objects will appear to move faster than objects further away, thus providing a cue to their distance. Objects nearer than fixations during head translation move in opposite directions on the observer's retinae, whereas objects further away than fixation move in the same direction as the observer's translation. For a moving observer, motion parallax is the most important visual cue for depth perception and seems to depend on the slow eye movement system (Nawrot, Nordenstrom, and Olson 2004)

2.3.3 Binocular cues

There are two types of binocular cues, which are binocular disparity (Figure 4) and convergence.

2.3.3.1 Binocular disparity

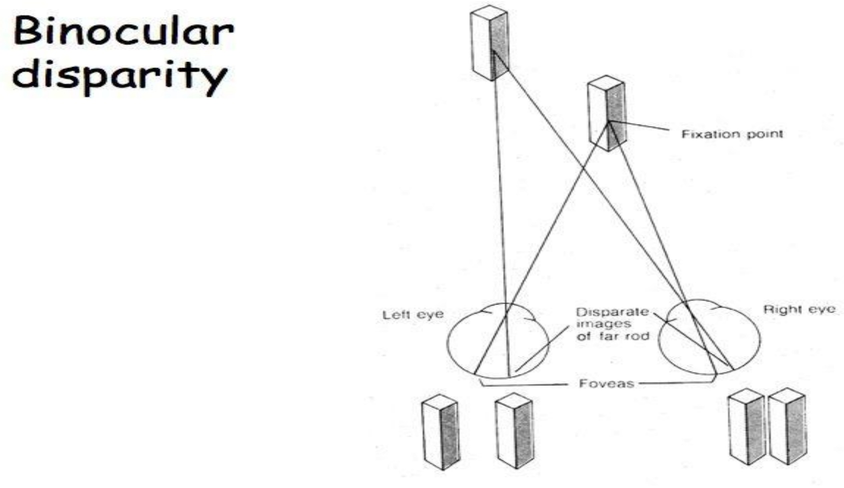


Figure 4: The depiction of binocular disparity

In binocular vision, the images that are projected onto the retinae of the left and right eyes are slightly displaced relative to each other. This difference is known as binocular or retinal disparity. They reflect the world from two slightly different vantage points(Qian 1997). Binocular disparities can be affected by factors such as gaze angle, viewing distance (retinal disparity increases with distance), eye alignment and the structure of the 3D world (DeAngelis 2000).

There are two types of binocular disparities that have been described: horizontal and vertical. Horizontal disparity is one of the most important and accurate depth cues that give rise to vivid depth perception (Qian 1997,Nieder 2003, Poggio and Poggio 1984). Vertical disparity is the difference in vertical extent of an image in one eye compared with the other (J. M. Harris 2004). The impact of vertical disparity is limited but may play a role in maintaining the ocular alignment and viewing distance estimation (Cumming 2002). The relative estimation of depth with respect to a fixation point known as stereoscopic depth perception or stereopsis (Greek for solid vision) was created by Wheatstone, the inventor of the stereoscope(Qian 1997) in the 19th century.

2.3.3.2 Convergence

Convergence is defined as simultaneous inward movement of both eyes to maintain a single binocular vision and this action is mediated by medial rectus muscle. On the contrary, divergence is the outward movement of both eyes and needs intact lateral rectus muscle. Generally, these both movements are classified as vergence in the ophthalmology world. In a nutshell, when a person looks at a closer object, the eyes will move towards each other (convergence) and the eyes will rotate away from each other (divergence) if the object is far away.

2.3.4 Proprioception

It is defined as the ability to sense stimuli arising within the body regarding position, motion, and equilibrium. For example, a person is able to figure out if the arm is above the head or not when the eyes are closed.

2.4 Methods to improve depth perception

Many methods have been researched in recent years for enhancing the surgeon’s perception of depth in the operative field. They include:

1. Stereoscopic endoscopy: the principle simply relies on two images with appropriate disparity being sent to each eye so when fused they can create the perception of depth.

   There are two ways to create endoscopic stereovision. One is by using a true stereo- endoscope (two cameras) and the other is by dividing one image stream into two using a prism. Relevant papers in regards of stereoscopic endoscopy have been discussed in the previous section under 2D vs 3D laparoscopy.

2. Digital image processing: this improves the contrast by digitally enhancing the outlines thereby creating a 3D effect.

   Other method for enhancing depth perception include digital enhancement of laparoscopic images achieved by real-time image processing, which improves the chromatic quality and 3D effect. Most digital cameras are equipped with this feature and the level of processing can change to improve different lighting conditions. Rene Wenzl et al (1998) demonstrated the advantages of this method during difficult endoscopic procedures which resulted in less blood loss, fewer unnecessary movements and no complications. Similarly, Kawaida et al (2002) showed the superiority of such endoscopic systems compared to conventional ones when used for diagnostic purposes.

3. Improving the quality of images: this allows for better visualization of finer details and texture and can improve depth perception

There have also been reports of use of high resolution digital cameras in laparoscopy (HDTV). Although the improved resolution cannot achieve the depth perception of stereoscopic systems, it still provides an advantage over conventional systems by improving the quality of the monocular cues described above (Bergen 1996).

4. Introducing shadow in the operative field: this compensates for the absence of an important monocular cue.

Shadow has been perceived as one of the important depth cue. The current system with light source at parallel with the scope diminishes the presence of shadow. Shadow creation needs light application from different angle rather than parallel form. Introducing shadows within the operative field has also been attempted. Hanna et al (2002) tested 20 medical students performing simple laparoscopic task using a Dundee Endoscopic Psychomotor Tester (DEPT). A secondary light source was introduced through a separate port from the camera so as to cast shadows within the operative field. The study demonstrated a significant improvement in task performance when shadow is introduced in the operative field.

Further work by Mishra et al (2004) also demonstrated the net advantage of the shadow inducing system on task performance and identified the optimal position and contrast for casting shadows. This was found to occur when the illumination was overhead (i.e. the shadow was in a vertically down position) with 22-44% shadow contrast.

Another paper studied the effect of colour shadow versus black shadow and they concluded that there was no difference between colour shadow and the black shadow but having a shadow (colour or black) increased the task performance to 10% in 3D laparoscopy compared to shadowless (Shimotsu and G. L. Cao 2007).

Depth perception is the main criteria in the assessment of laparoscopic surgical skills among surgeons which is known as Global Operative Assessment of Laparoscopic Skills (GOALS). This global rating scale was developed by Vassiliou et al (2005). The GOALS consists of testing of five domains, namely depth perception, bimanual dexterity, efficiency, tissue handling and autonomy. GOALS has been validated for laparoscopic cholecystectomy, laparoscopic appendectomy, groin hernia, incisional hernia repair and the list is growing. GOALS has been found to be both valid and reliable.

2.5 Measurement of force in surgery

Force is an important element in surgery. The process of gripping, dissecting, pushing and pulling tissues require a significant amount of force. The force has to be in the appropriate level to execute the surgical task. A hard force may cause tissue trauma and a light force would not be effective. There are many ways to measure force in surgery. Hanna et al (2008) published a paper about force measurement system in surgery in the Journal of Surgical Endoscopy. The system composed of sensors mounted on a forceps handle, a port force direction assembly, an electronic interface comprising isolation and output conditioning electronics, an analogue to digital converter, and a dedicated software to record and display results.

This force measurement system was developed for use with standard instruments in clinical practice. It is designed to be suitable for use with a variety of instruments with different jaw configurations, able to accommodate 5.5-mm port, autoclavable, and finally able to measure the total force at the instrument tip as well as the force vector at the port site.

Measuring force in surgery has many applications. The force feedback system with video recording will provide a good feedback tool for teaching and training purposes to refine laparoscopic movement and tissue handling. In addition, the system would assist to correlate force data with indicators of surgical parameters to highlight performance-shaping factors which includes technical errors and tissue trauma. It can also be used to define force patterns incurred during certain surgical postures, the effect of muscle fatigue, and port locations. The combination of force pattern and parameters of mental workload can be used to indicate the level of psychological stress during surgical procedures. However, there are many drawbacks with force measurement system. The force measurements by the port direction assembly depend on the thickness and elasticity of the abdominal wall, which is influenced by the pressure of pneumoperitoneum and port location. Furthermore, the force exerted by the surgeon will depend on the intra-corporeal to extra-corporeal instrument ratio.

2.5.1 Tactile sensing technology and haptic feedback in laparoscopic surgery

The measurement of force in surgery will not be possible without the concept of tactile sensing which was introduced and studied extensively in the mechatronic field. Any device which senses information such as shape, texture, softness, temperature, vibration or shear and normal forces, by physical contact or touch, can be termed a tactile sensor. Haptics is a general term referring to cutaneous (tactile) as well as kinesthetic (force and position) information. The haptic feedback (tactile and force) are desirable in laparoscopic surgery and help surgeon to have an idea about the texture and the force of the manipulated tissue. There are many tactile sensing techniques such as strain gauge, capacitive, piezoelectric, piezoresistive, optoelectric and multiple component sensor. The strain gauges system is one of the widely used system and cheap (Tiwana, Redmond, and Lovell 2012). The Hanna’s force measurement system utilized strain gauges method.

There are two methods on how the force can be measured. These are known as direct and indirect force sensing methods. The force sensor is attached at the end of the laparoscopic instrument in the direct method and the sensor is located in the handle of the instrument in the indirect approach. These two approaches have both advantages and disadvantages. One study from the Netherlands concluded that indirect method with the sensor over the shaft of the instrument was able to estimate best measurement of pinch and pull forces at the grasped tissue. (J.John et al. 2012)

2.6 Measurement of time in surgery

Time is an important factor in the surgery and an expert surgeon is able to perform the surgical task with shorter performance time and minimal or no complication. Thus, control and awareness of time in surgery are particularly critical factors for patient safety, technical and organizational constraints (Nyssen 1996). There are two distinct features which need to be differentiated in the study of time. These are time performance or execution time and time estimation. Time performance is defined as time spent on doing a task and time estimation is when the subject is asked to estimate the time that the subject spent on executing the task. This time definition is widely studied in the ergonomics field.

2.6.1 Time estimation paradigm

In the study of subjective duration, there are two distinct paradigms: the prospective paradigm, in which participants know in advance that they will have to judge the duration of a time period, and the retrospective paradigm, in which participants do not know until after a time period that they have to estimate its duration. In both cases, participants experience a time period in passing, but there are differences in the cognitive process that are involved. In the prospective paradigm, a person will try to remember the duration and relate with the previous experience of time period. On the contrary, a person in the retrospective paradigm needs to estimate time from the stored memory. In gist, prospective paradigm is based on attentional capacity and the other one is explained by memory retrieval (Block 1997).

One interesting study by Blavier and Nyssen (2009) in the Journal of Ergonomics evaluated the impact of 2D and 3D images on time performance and time estimation during a surgical motor task. They studied 60 nurses (without surgical experience) and 20 surgeons and they were asked to perform a surgical task in 2D and 3D system. Their time performance during the task were measured and they were asked to verbally estimate their time performance. The results showed faster performance in 3D than in 2D view for novice subjects while the performance in 2D and 3D was similar in the expert group. In 2D condition, all subjects accurately estimated their time performance while they overestimated it in the 3D condition.

2.7 Measurement of volume in surgery

The idea of volume estimation becomes relevant with the growing popularity of bariatric surgery. Regardless of the type of weight loss surgery (restrictive, malabsorptive or both), the attending surgeon needs to create a small gastric pouch to minimize the failure of bariatric surgery. However, till now there is no objective and reliable way of measuring the gastric volume and it is entirely hinged on surgeon’s discretion.

2.8 Measurement of curvature in surgery

The notion of curvature measures how sharply a curve bends. We would expect the curvature to be 0 for a straight line, to be very small for curves which bend very little and to be large for curves which bend sharply. In other words, the curvature of a circle is the inverse of its radius. Small radius creates sharp curve and large radius will create a smaller curve. Till date, there is no literature on the measurement of curvature in surgery.

2.9 Summary of literature review

From the literature review, we can conclude that most of the papers managed to prove beyond reasonable doubt that 3D laparoscopic system brings out the best surgical task performance compared to 2D imaging. The endpoint of these assessments are made based on performance time and the number of errors. The research on the influence of force and time in laparoscopic surgery is well established. Nevertheless, the study of depth perception, especially in the form of angle, area, curvature, volume, distance and spatial coordinates is not done as an independent factor. The influence of these factors on the performance of 2D and 3D laparoscopic surgery needs to be elucidated. Apart from that, there was no study on the effect of eye exercises on 3D laparoscopy.

CHAPTER 3

Chapter 3 Methods and materials

3.0 Overview

The effect of the following six components: angle, area, distance, volume, curvature and spatial coordinates was studied independently in the execution of the surgical task. Each component except spatial coordinates was assessed by the method of measuring, comparing and creating. The measurement task tested the ability of the participant to estimate a given measurement in any of the components. The comparison task assessed how the participants could compare the given components of varying measurements. The creation task involved the ability of the participant to create a given measurement in selected (distance, angle and volume) components. Besides that, we devised a spatial coordinates test to assess the significance of coordinates in 2D and 3D.

All the students went through the visual acuity test, eye deviation test and visual analogue score (VAS). Visual acuity test was done using standard Snellen chart. The Snellen chart was plastered at the wall in the experiment room at 3m distance from the student. The visual acuity was assessed for both eyes, left eye while covering the right eye and vice versa.

Eye deviation was measured with Maddox Wing device (Figure 5). The Maddox Wing is a simple test to measure the horizontal and vertical eye deviation. The horizontal eye movement which is more important clinically is measured with the student looking through the eyepiece of the device. As the eyes are engrossed in the vertical arrow, there will be a fluctuation of the horizontal measurement above the arrow. The deviation is read when the arrow fluctuates at the same digit which may be positive or negative digit. This will be the horizontal deviation of the eyes.

The visual analogue score was a simple numerical score to assess presence of eye strain, visual or other related symptoms. The score ranged from zero (no symptoms) to the varying level of intensity (from 1 to 10). For example , if a student reported no headache , then the score will be zero , mild head headache ranged from 1 to 4 , moderate headache from 5 to 7 and severe headache from 9 to 10.

The students were randomised between 2D and 3D imaging test to begin with. All students completed 2D and 3D imaging experiments. The students started with spatial coordinates test for a minute and then proceeded with components test as described in Table 2. Before the components test, the visual analogue score and eye deviation test were measured again. The reason for the repeat measurement for visual analogue score and eye divergence test at every stage is to identify any inherited difference in eye divergence in the population and to see any changes of eye symptoms/divergence with 2D, 3D environment and eye exercises.

The 3D imaging arm was randomised into two groups: those who received eye exercise and those without eye exercise before the imaging. The entire experiment is depicted in the flow chart. The components tests had been summarised in the Table 2.

Figure 5: Maddox Wing device

3.1 Research methods

A prospective, randomized study in a purpose built, state of the art laboratory setting based at the Cuschieri Skills Centre (CSC).

3.2 Power calculation, Subjects and recruitment

Using sample size calculation, with power of 80%, alpha - 0.05, and the mean differences between group of 0.5, we need at least 22 participants for the experiment. Hence we chose 24 medical students from University of Dundee for this study. There was no specific inclusion or exclusion criteria. The study was advertised in the university website and at the medical library.

3.3 Setup of experiment

The experiment was done using a standard pelvic trainer at the purpose-built Cuschieri Skills Centre, Ninewell's Hospital, Dundee. The 2D and 3D surgical imaging were provided by Storz HD advanced laparoscopic system which was on loan by Karl Storz GmBh to Cuschieri Skills Centre. The advanced laparoscopic system had both 2D and 3D technology which can be switched to according to the needs. The following aspects were standardised for the experiments while taking account into the ergonomics of laparoscopic surgery:

1) The distance between the endoscopy and the target – 10cm

2) The distance between the participant and the screen – 1m

3) The location of the screen level - the same level or 15 degree less than horizontal to the participant (Reading position)

4)10mm thirty degree laparoscopy, 30cm

5) All the working instruments were 5mm, 30cm.

6) The manipulation angle was 60 degree. (The angle between the two working instruments).

7) The elevation angle was 60 degree. (The angle between the laparoscope and the horizontal level).

8) Intracorporeal to extracorporeal instrument length ratio is more than one.

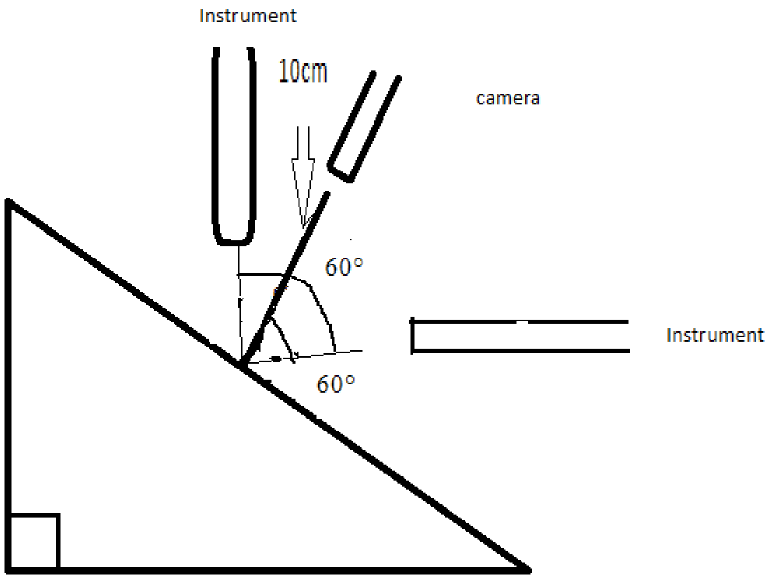


Figure 6: The schema of the laparoscopic instruments during the experiment

Optical axis to target view angle was 90 degree.

The manipulation angle was 60 degree. (The angle between the two working instruments).

The elevation angle was 60 degree. (The angle between the laparoscope and the horizontal level).

3.3.1 Materials and equipment

- Laparoscopy HD 2D and 3D system from Karl Storz GmBh & Co, Tuttlingen, Germany (19 inch, resolution 1920x 1080 pixels)
- Thirty degree 10mm laparoscope
- Two 5mm laparoscopic graspers
- Cardboards for the creation, comparison and the measurement tasks.
- Foley's balloon catheter- 12F,14F,16F
- Velcro tape
- Neopolene sheet
- Syringes - 5ml, 10ml
- Multiple small clay balls
- Strings
- Maddox Wing device
- Snellen Chart

- Pelvic Trainer box
- 3D glasses
- Multiple color stickers
- Mathematical instrument set – protractor, compass.

3.3.2 Randomisation

The simple randomization in the experiment was first done for the surgical imaging, 2D or 3D and secondly, within the 3D group to randomize the students to see the effect of eye exercises.

3.3.3 Ethical considerations

The study was reviewed and ethically cleared by Research Review Committee, University of Dundee. As the study did not involve patient's health records, the Caldicott guardian approval was not needed in the study. Before the student embarks on the experiment, he or she is required to go through the Participant Information Sheet and sign the consent form.

3.4 Flow chart

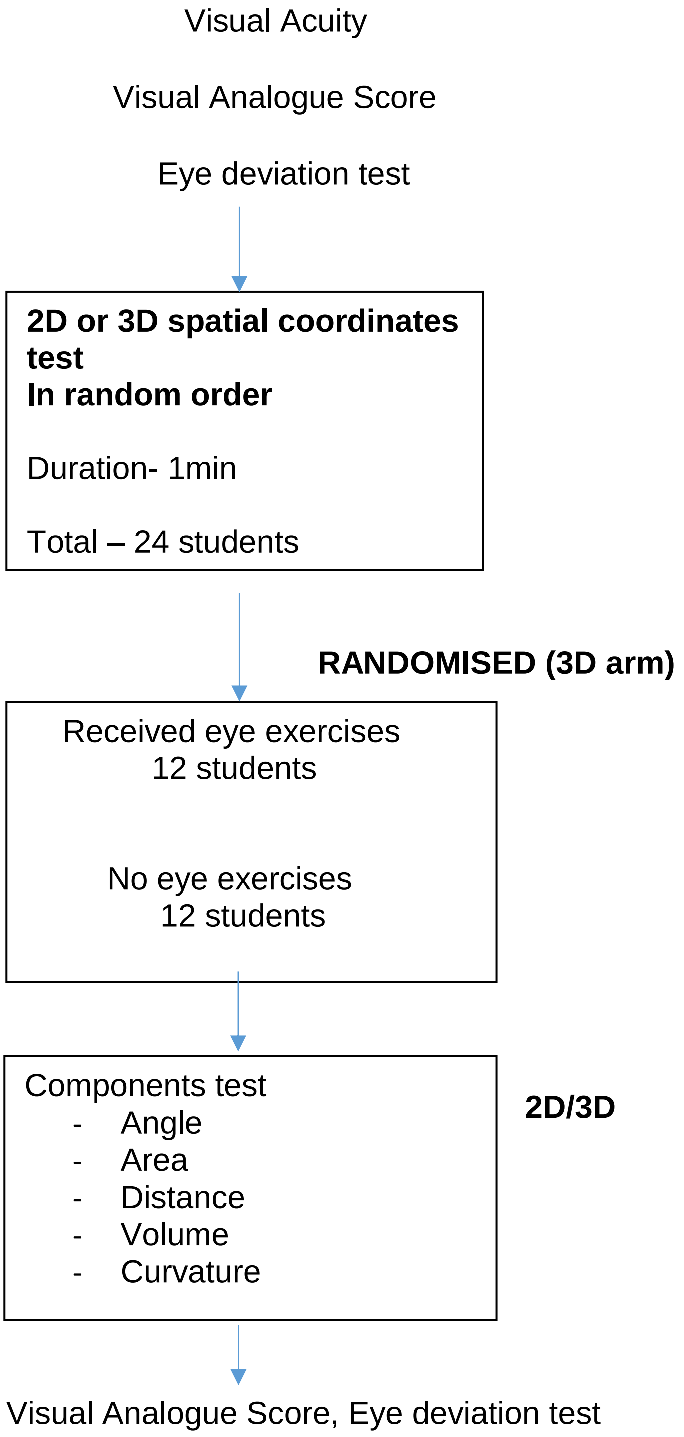


Figure 7: Flow chart of experiment

3.5 Protocol Design

3.5.1 Overview of component test

Component	Creation	Comparison	Measurement
Area Ref- 1.5cm	Omitted due to task complexity	To compare areas of different squares and circle – within 0.15cm /0.2cm increments Square 4/4.15/4.3/4.45/4.6 cm (each side) Circle – 4/4.2/4.4/4.6 cm (diameter)	To measure area of given square and circle Square – 4/6/7/9cm (each side) Circle – 5/6/7/9cm (diameter)
Distance Ref- 1.5cm	To create a distance of 2/3.5/4.5/6 cm	To compare distance of 4.0/4.15/4.30/4.45cm	To measure a given distance 4/6/7/9 cm
Curvature	Omitted due to task complexity	To compare a curvature The curvature is created with changing the radius from 3/4/5/6cm	Omitted due to task complexity
Angle Ref – 15 degree	To create following random angle 5/30/50 degree	To compare different angle 30/32/34/36/38 degree (the sides of each angle will be 4cm in length, 3mm width)	To measure the following drawn angles one at a time 25/ 35/45/65

Volume Ref- 2ml	To create a volume by injecting Foley's balloon catheter. Volume- 3/5/8ml	To compare volumes of different balloon 3/4/5/8ml	To measure the given volume 3/5/7ml

Table 2: Overview of components test

3.5.2 Distance creation

For the distance creation, we created a string with tiny paper enclosing a small portion of it. The paper was movable along the string and the participant needed to move the paper to the estimated distance using the laparoscopic grasper (Figure 8). Beneath the model, we pasted the standard reference scale for the distance which is 1.5cm to guide the student on the range of dimension. Then, the images were snapped in the respective groups and the distance was measured from the images. The images of the distance were magnified between 2 to 2.5 times and it affected the exact measurement of the distance. There was an option of measuring the distance directly from the experiment field by removing the camera and the neopolen sheet, but it was very tedious and time consuming. Thus, the actual distance from the snapped images was calculated with the known reference scale (1.5cm) using a simple ratio calculation. The test took approximately 15 to 20 seconds.

3.5.2.1 Choosing the specific dimension for distance creation

This trial of experiment helped to choose the specific distance for assessment of distance creation. The distances were cut into the following measurement and mixed. The participants were

asked to arrange the distance from the smaller to the bigger value in an open environment.

Distance	Percentage of increment
4.0cm, 4.2cm, 4.4cm and 4.6cm	5%
5.0cm, 5.2cm, 5.4cm and 5.6cm	4%
6.0cm, 6.2cm, 6.4cm and 6.6cm	3.3%
7.0cm, 7.2cm, 7.4cm and 7.6cm	2.9%

Table 3: The different distances with the corresponding percentage increments

We found that once the distance got bigger, the task of comparing and arranging the lines became difficult. This was due to the fact that once the distance of the line was increased, the percentage of increments dropped and that made the task difficult. This experiment guided us to choose the dimension 4cm to study the distance component and bearing in mind about the size of a standard pelvic trainer which was 50cm x 18cm x 10cm. Despite the fact that a larger distance would create a harder task but a moderate size was chosen as it could accommodate the pelvic trainer and yet could make the task difficult.

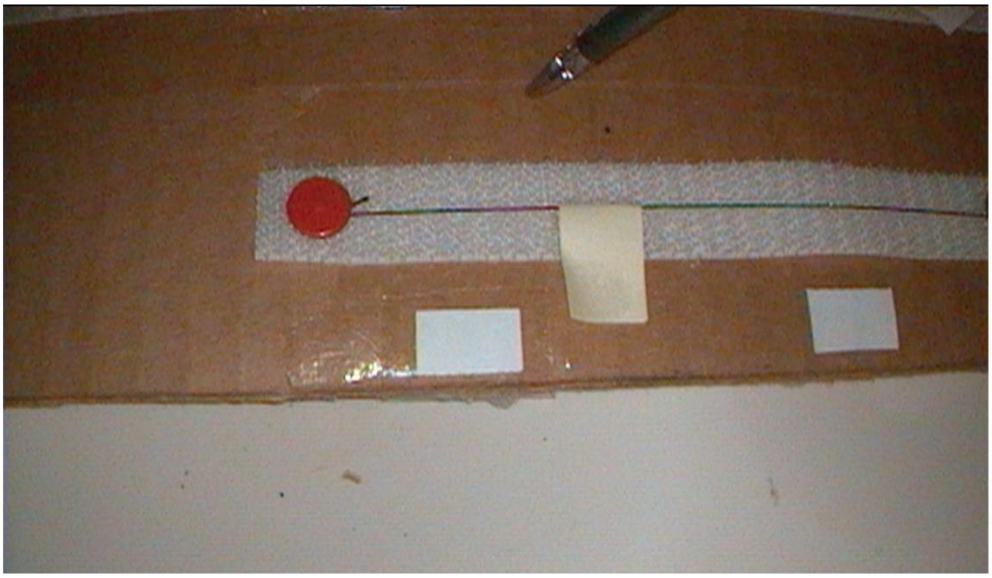


Figure 8: The creation of distance

The horizontal distance of the rectangle in the figure was 1.5cm (as a reference scale).

3.5.3 Angle creation

For angle creation, we devised a simulated angle creator model using a card and thumb tack. The movement of the card with one corner fixed with tack created an angle (Figure 9). The student needs to move the card to the desired angle using the laparoscopic grasper. For angle, there was a reference angle which was 15 degree that was embedded beneath the model. For laparoscopic 2D and 3D group, we snapped the images and measured the angle using the protractor. While the distance component revealed magnification in the snapped images, but the angle component was constant. The test took approximately 15 to 20 seconds.

3.5.4 Volume creation

For volume creation, we used Foley's catheter and we injected air into Foley's by following the instructions from the participant (Figure 10). The reference volume for this task was 2ml. The test took approximately 15 to 20 seconds.

3.5.4.1 The endpoints of creation test

The endpoints of the creation test - the deviation of endpoints from the actual result in components test in 2D imaging and 3D imaging.

1. For the creation test– the endpoint was the actual deviation from the result. For example, if the actual measurement was 5cm and a participant estimated as 5.5cm, the deviation was + 0.5cm. If another participant estimated the distance as 4.5cm, then the deviation was –0.5cm.

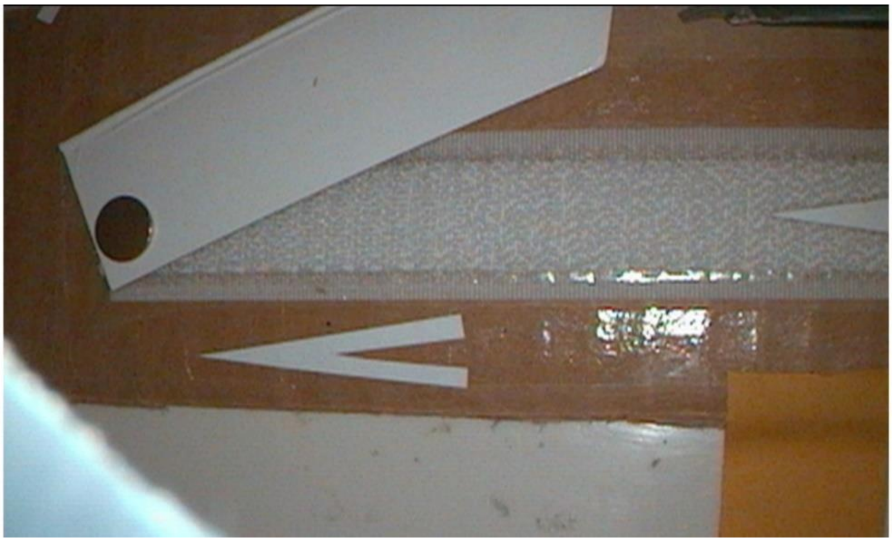


Figure 9: The creation of angle

The angle which was showed by small paper was 15 degree (as a reference scale)

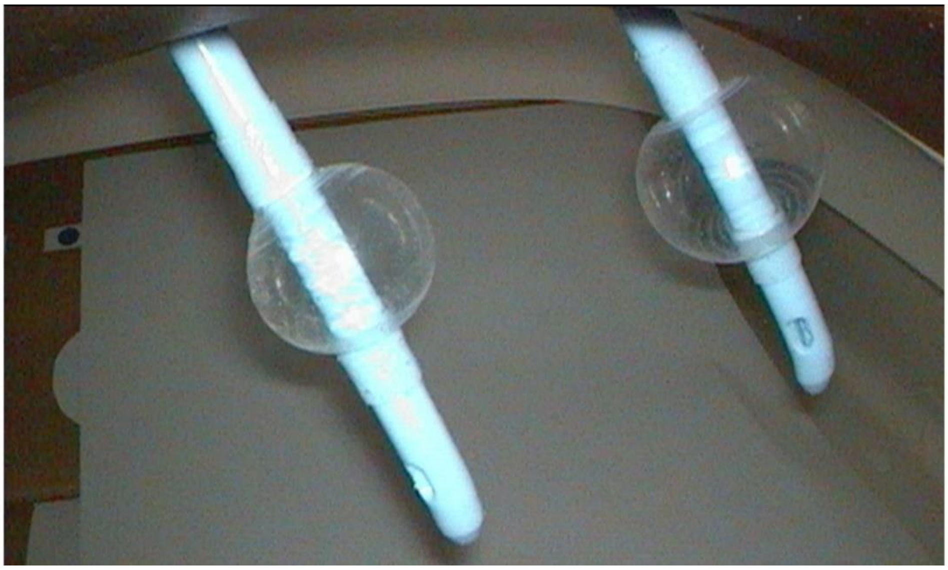


Figure 10: The creation of volume

The Foley's in the left side of the picture was the reference scale (2ml)

3.5.5 Comparison test

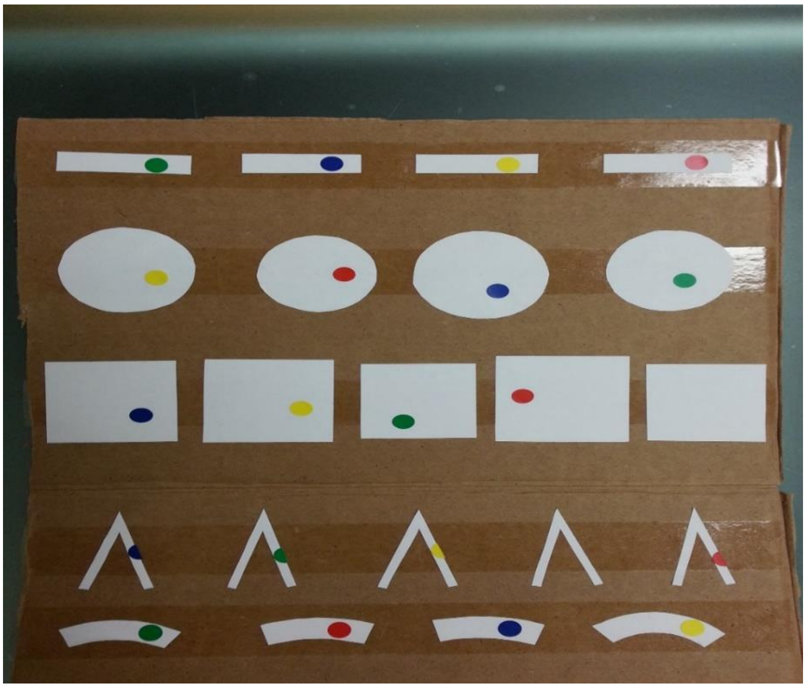


Figure 11: Comparison test

The comparison test generally involved papers which had been cut according to the different shapes and measurement and were labelled with various colours for the identification (Figure 11). The increments of the dimension were narrow to increase the difficulty of the tests. The participant was asked to arrange the colour sequences (red, green, blue, white, yellow) for all the components from the smallest to largest dimension. For curvature component, participant was asked to arrange from the less curve (flat) to more curve (sharp). The comparison test was done for all the components and each test took approximately 15 to 20 seconds.

3.5.5.1 Volume comparison

For the comparison of the volume, Foley's balloons were inflated with four different volumes - 3ml, 4ml, 5ml and 8ml and participant was asked to compare the volumes. All the four balloon were colour coded and the participant needs to arrange the sequence from the smaller volume to the bigger volume. The test took approximately 15 to 20 seconds.

3.5.5.2 The endpoints of comparison test

In comparison test, the number of sequence which was guessed correctly was calculated. For example, if two colours were correct out of four options, then the result would be 2/4.

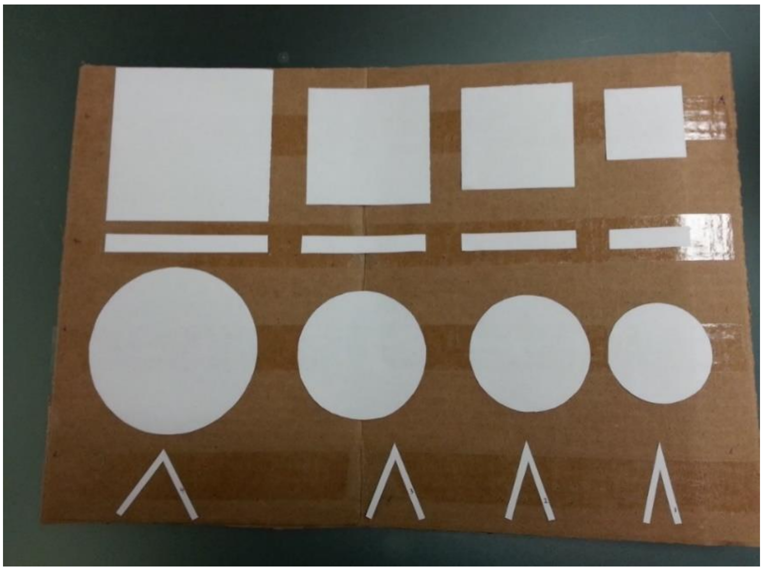


Figure 12: Measurement test

Again, papers of different shapes, dimension and angle were cut and arranged on the card board. The participant was given a reference scale to guide the measurement task. The participant was asked to estimate the length of the square (square), diameter of the circle (circle), length of the rectangle (distance) and the angle of different dimensions. The each test took approximately 15 to 20 seconds.

3.5.6 Choosing a specific dimension for area (square and circle)

Trials of experiments using a square in the following dimension used to study the influence of the area.

Dimension at 4cm and increments	**Area**	**Percentage of area increment**
4.0x4.0cm	16	-
4.15x4.15cm	17.2225	7.098
4.3x4.3cm	18.49	6.855

Table 4: The dimension at 4cm and more with the corresponding area increments

Dimension at 5cm and increments	Area	Percentage of area increment
5.0x5.0cm	25	-
5.15x5.15cm	26.5225	5.74
5.3x5.3cm	28.09	5.58

Table 5: The dimension at 5cm and more with the corresponding area increments

Dimension at 6cm and increments	Area	Percentage of area increment
6.0x6.0cm	36	-
6.15x6.15cm	37.8225	4.819
6.3x6.3cm	39.69	4.705

Table 6: The dimension at 6cm and more and the corresponding area increments

We concluded that when the area of a square was increased, the percentage of area increments fell and thus the task became difficult. This experiment helped us to choose 4cm as the basic level for both square and circle component study.

3.5.7 Volume measurement

The Foley's catheter was injected with specific volumes (3ml, 5ml and 7ml) and was placed next to the reference volume (1.5ml) and the student was asked to measure the volume. The test took approximately 15 to 20 seconds.

3.5.7.1 Choosing a specific dimension for volume

The volumes for the measurement task were initially assigned as 12ml, 20ml and 25ml. During the experiment, the silicon Foley's catheter was noted to accommodate comfortably up to 12 ml. It was possible to inject more volume and stretch the balloon but the air gradually leaked from the outlet. Thus, the volumes were modified into smaller values which were arbitrarily agreed as 3ml, 5ml and 7ml.

3.5.8 The endpoints of the measurement test

The endpoints for the measurement test were the deviation from the actual measurement of the tests. The results of the component test was compiled in a separate sheet.

3.5.9 Spatial coordinates test

The spatial coordinates test was created using eight small clay balls which were numbered from one to eight and were suspended from the top in a pelvic trainer using strings at different coordinates. The different coordinates were created randomly and was made sure that the entire coordinates was visible from laparoscope. The student was required to touch the object laparoscopically using a grasper in 2D and 3D imaging with simple and straightforward rules (Figure 13)

The rules were as following;

a) Using dominant hand,

b) Touching fixed random sequence objects alternately (objects 1, 3, 5, 7 and objects 2, 4, 6, 8),

c) Avoid touching other objects or strings,

d) Completing the task within one minute.

The spatial coordinates test were video recorded and analysed using Human Reliability Analysis (HRA).

3.5.9.1 The endpoints for spatial coordinates test

The endpoints for the spatial coordinates test were the errors committed (type and number of error), number of movements and number of objects that the participant could touch correctly within the one minute. The type of errors in spatial coordinates test were as following:

1. Pastpointing
2. Not reaching the object
3. Touching the wrong object or the string

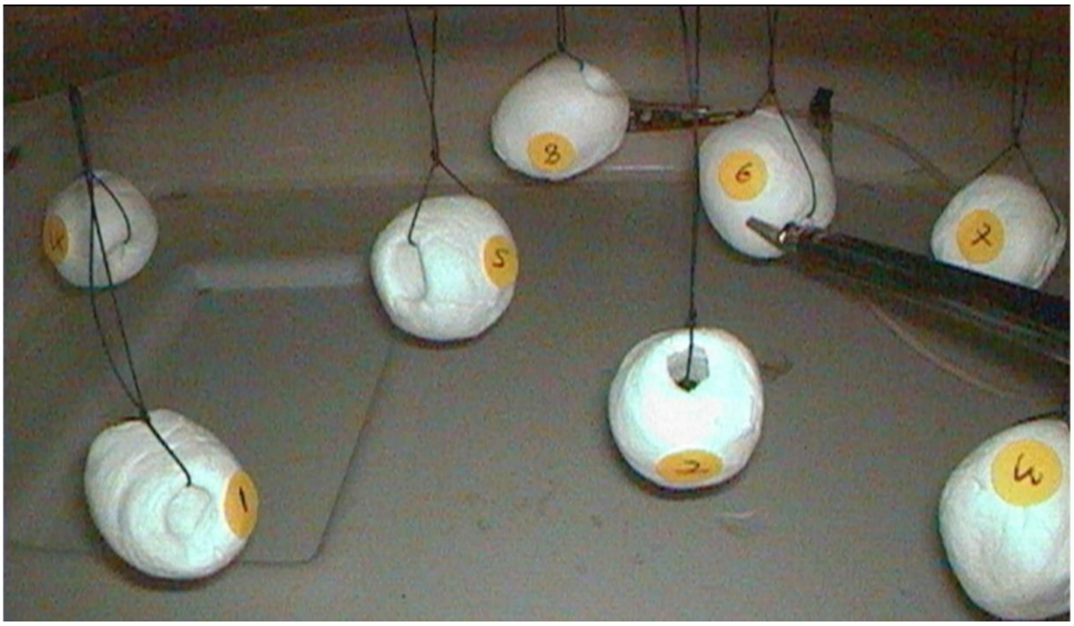


Figure 13: The spatial coordinates test

There were 35 components test in one arm and a participant had to complete 70 tests in both 2D and 3D. Thus, the projected duration for the entire experiment with informed consent was approximately 25 minutes. The total number of tests were 72 which included two spatial coordinates test in 2D and 3D.

3.5.9.2 Pilot study

Four medical students were involved in the pilot study and pilot study helped to identify the shortcomings in the study and facilitated the improvement of the study design.

3.5.9.3 Improvements on study design with pilot study

The pilot project was done based on three environments: open surgery (open 3D), laparoscopic 2D and laparoscopic 3D. The experiments took almost 90minutes and the participants became tired and they were losing the concentration at the end of the test. The fatigue may deviate the results and will complicate further participants' recruitment. Thus, the open 3D arm was removed from the experiment and the study was improvised especially in the creation, comparison and the measurement task, so these components test can be performed in a short duration but efficient manner. Now, the entire experiment can be accomplished in 25minutes (including the duration for the informed consent, explanation on the test and method to use Maddow Wing device)

At initial planning and pilot project, the effect of eye exercise was assessed after 3D components test and thus phase two was created, in which those who had eye strain symptoms in 3D arm were identified and subjected to eye exercise (phase two) and then five minutes 3D spatial coordinate test. However, the introduction of eye exercises at the end of the 3D spatial coordinate or components test did not serve any purpose. Thus, the five minutes spatial coordinate test was removed entirely and the eye exercises was brought before the 3D one minute spatial coordinate test. The participants who did and did not receive eye exercises were randomized and subjected to one minute 3D spatial coordinate test then followed by components test. In this way, any notable differences of eye exercises in the 3D imaging could be discerned.

Pilot project was pivotal in highlighting several weakness in the experiment and the study design was modified and fine-tuned at the end. The pilot study was done with the following sequences; open surgery first, then followed by 2D and finally 3D. The setback of this sequence was the presence of potential confounder which might mask the actual impact of a particular surgical imaging. For example, when the 3D imaging was studied at the end as per the initial method there was a possibility that any differences in the performance in 3D might be influenced by 2D imaging which was done prior to 3D. Thus, the better option was to alternate the sequence of the laparoscopic 2D and laparoscopic 3D experiments (randomisation) since the open surgery experiment had been omitted in final study.

Besides that, the pilot study confirmed that the dimension of angle was not magnified in 2D or 3D imaging. This was important as another component, the distance was magnified between two to three times in the 2D and 3D surgical imaging compared with actual measurement in open 3D field. The angle was not magnified as angle, mathematically was formed when two separate lines crossed to each other. Thus, only the separate lines were magnified but the dimension that was formed when it crossed; the angle, stayed static. In clinical practice, this finding may give a clue when a need arise to reach certain body structures at a different angle, keeping in mind that angle would not be magnified.

3.6 Statistics and data analysis

The statistics analysis were done with both descriptive and inferential statistics using SPSS IBM 22.0. The normality test of Kolmogorov Smirnov study revealed normal distribution and thus parametric test and mean was used to depict the study results. The paired t-test was used to study the mean difference between generic components in the 2D and 3D imaging group. The independent t-test was used to analyse the effect of eye exercise on visual symptoms. A p value less than 0.05 was accepted as statistically significant. The histogram with error bars were used to represent the study results graphically.

3.7 Visual analogue scale for eye symptoms (VAS)

0 2 4 6 8 10

0- None

2- Annoying

4- Uncomfortable

6- Dreadful

8- Horrible

10-Agonising

The symptoms are as following:

Blurred vision	Y/N
Difficulty in refocusing from one distance to another	Y/N
Irritated or burning eyes	Y/N
Dry eyes	Y/N
Eyestrain	Y/N
Headache	Y/N

Dizziness Y/N

Participant is required to inform any other eye symptoms if found during the experiment.

3.8 Eye exercises for 3D imaging

The eye exercises were quick, simple and took around two minutes. There were total three exercises performed by the students in the 3D arm.

a) Palming eye relaxation technique

Participant would sit on a chair and make himself comfortable. He would rub his hands until they warm up. Then, he would close his eyes and cover them with the palm of his hands without pressing hard on his eyes. He would then breathe deeply. This exercise would be done for a minute.

b) The two dots vision exercise

A chair was placed at about 10 feet away from a wall. The participant would sit comfortably and take a deep breath and relax. Medium sized circles were cut and pinned to the wall approximately one and half meter apart. The participant needed to focus at one of the dots for a few seconds, and then slowly move his eyes to the other dot. He had to repeat this exercise for a minute. Then, after one minute, he had to close his eyes and relax.

c) The eye blinking exercise

The participant would close his eyes and relax. He would blink 15 times rapidly. He would be asked to blink lightly as if the eyelids are the wings of a butterfly. Then, he had to close his eyes and relax. He had to repeat this exercise twice.

CHAPTER 4

Chapter 4 Results

4.0 Results

The total of 24 medical students were involved in this experiment. There were 20 males and 4 females.

4.1 Descriptive statistics

The following table shows the descriptive statistics for selected variable- distance creation 2D in the experiment. The distance creation 2D (distance cr2d) was analysed to depict the data normality.

Distance creation 2D	**Statistic**
Mean	0.057
Standard deviation	0.679
95% confidence interval	-0.229 to 0.344
Skewness	0.477
Kurtosis	-0.193

Table 7: Descriptive statistics of distance creation 2D

Normality test	**P value**
Kolmogorov- Smirnov	0.2
Shapiro-Wilk	0.305

Table 8: Normality tests

There were some results variation in the Kolmogorov- Smirnov and Shapiro-Wilk test as the sample size was small. However, the histogram and Q-Q plot for distance creation 2D showed almost near normal data distribution. Thus, normal distribution was assumed and parametric tests were used for the analysis.

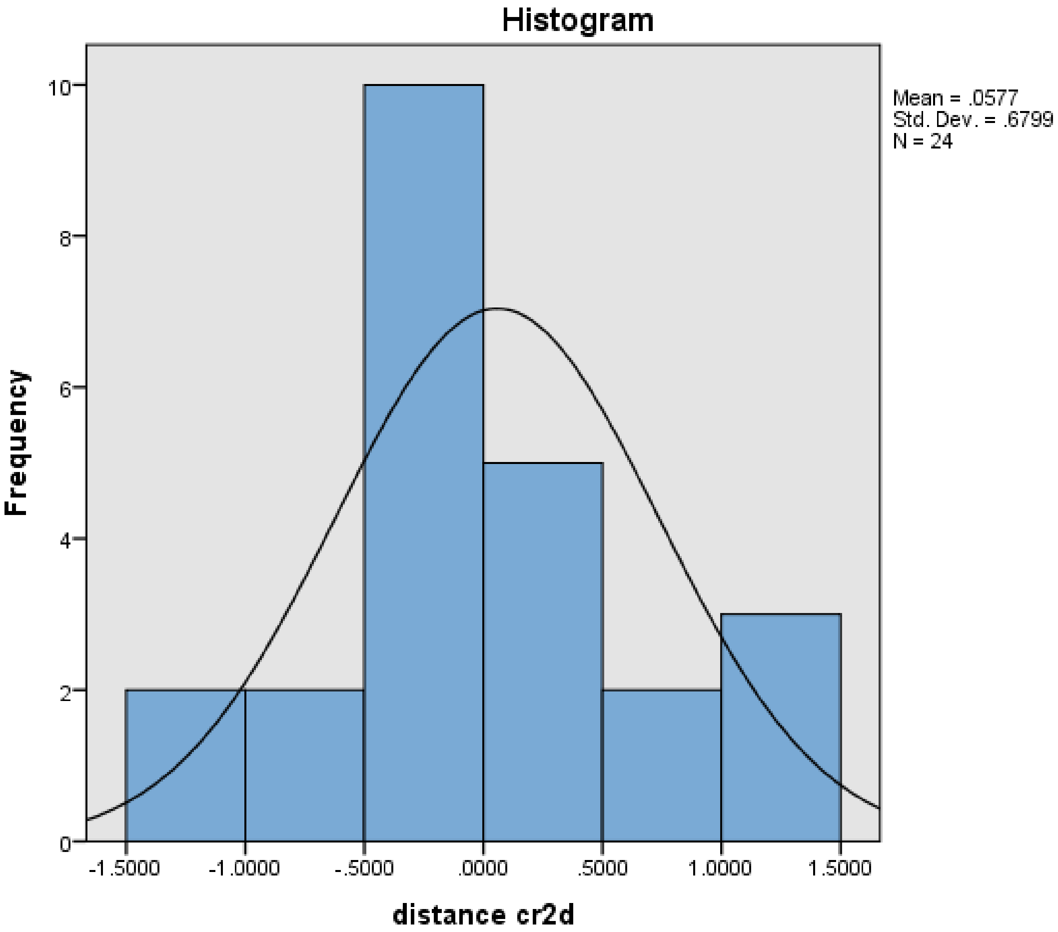


Figure 14: Histogram of distance creation 2D

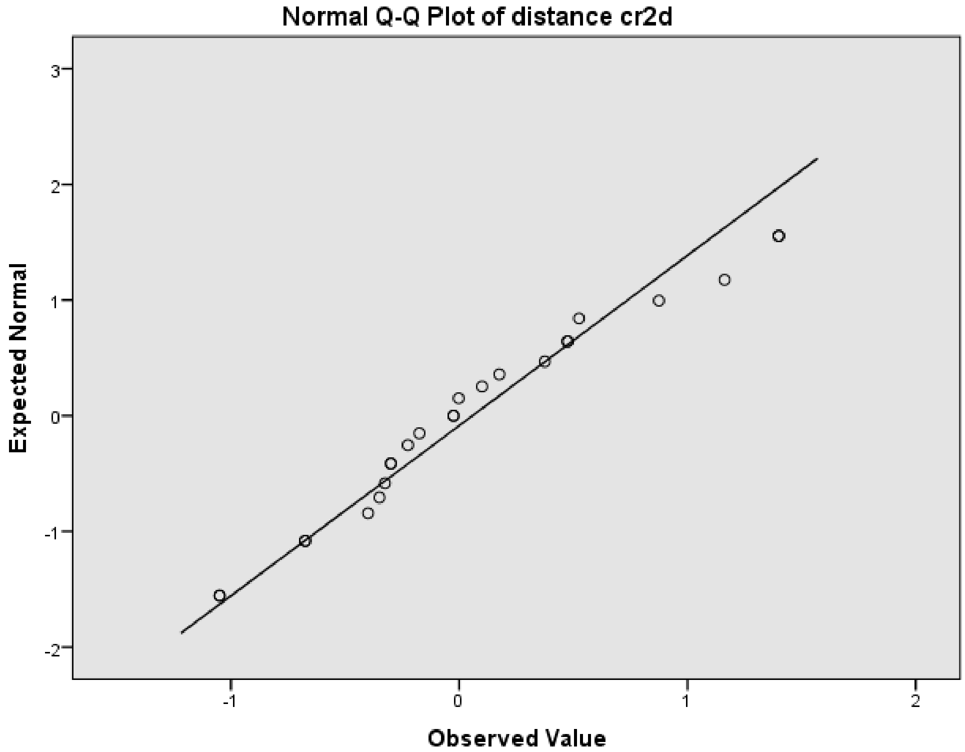


Figure 15: Normal Q-Q Plot of distance creation 2D

The results were grouped and analysed according to the individual components. The results were analysed between the groups 2D and 3D surgical imaging and in between the different values within each group.

4.2 Distance

4.2.1 Distance creation

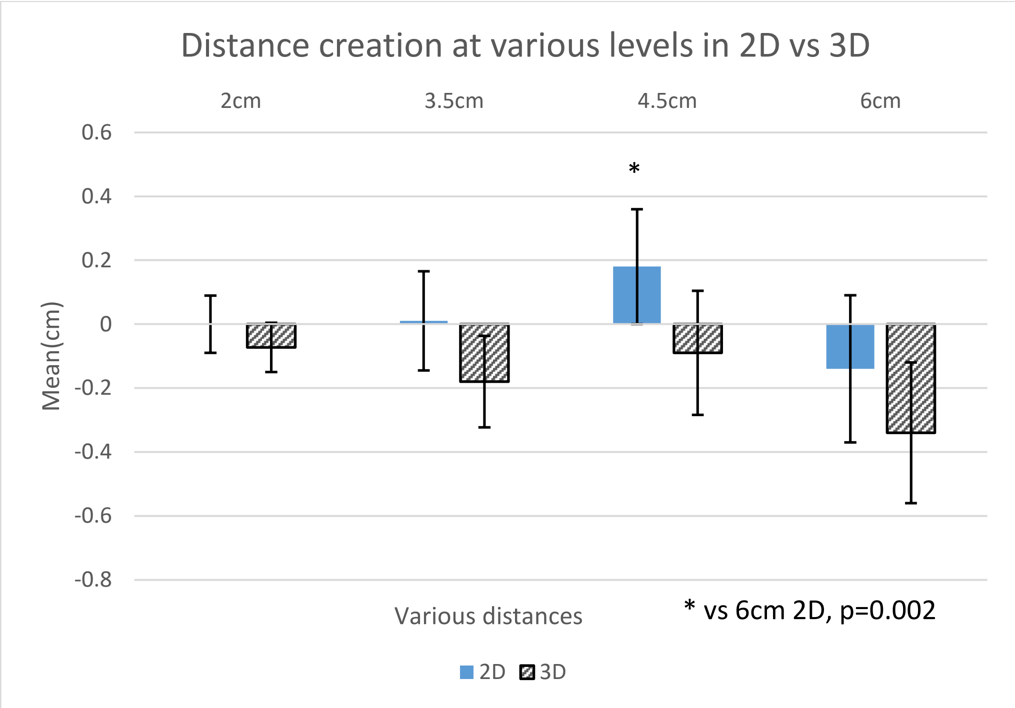


Figure 16: Histogram of distance creation at various levels in 2D vs 3D

There was no statistically significant difference between the 2D and 3D imaging in the distance creation. The most accurate level for distance creation was 2cm. It is apparent that the distance creation is underestimated in the 3D imaging due to the negative values. In 2D, only 6cm group was underestimated. For within group analysis, there was no significance difference between the value of 2cm vs 3.5cm, 2cm vs 4.5cm, 2cm vs 6cm, 3.5cm vs 4.5cm and 3.5cm vs 6cm in 2D or 3D surgical imaging. However, there was a significance difference between 4.5cm vs 6cm in the 2D with p value of 0.002 but not in 3D imaging.

4.2.2 Distance measurement

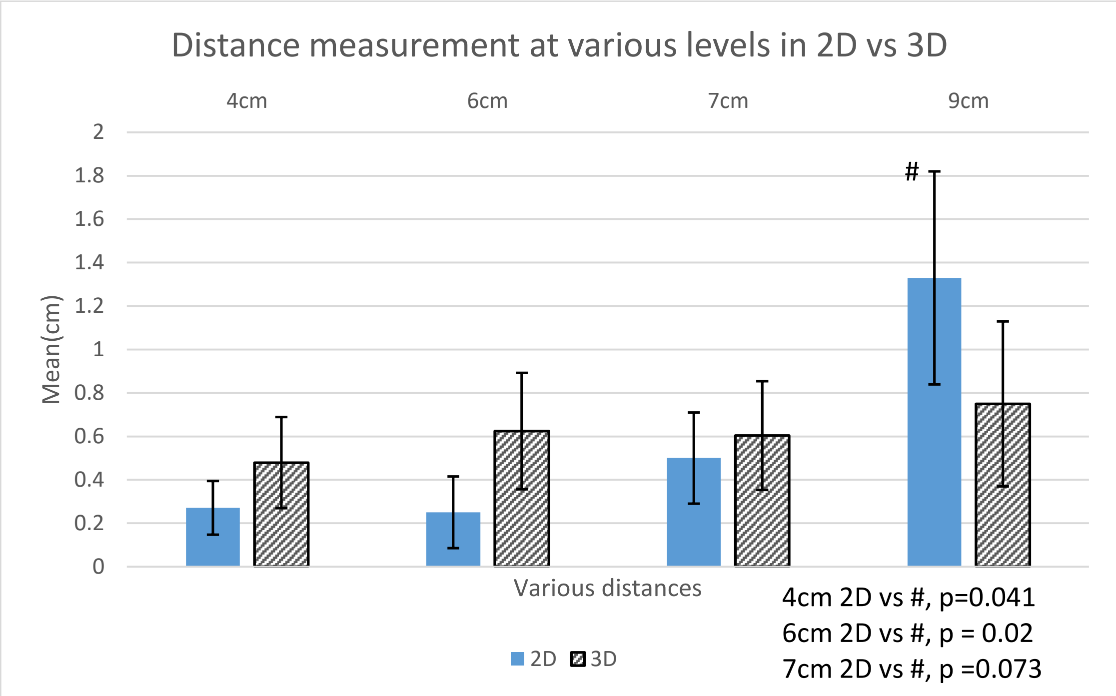


Figure 17: Histogram of distance measurement at various levels in 2D vs 3D

The most accurate level for distance measurement was 4cm.The distance measurement showed overestimation in both 2D and 3D surgical imaging. There was no significant difference between the 2D and 3D imaging at any level. For the within group analysis, there was a difference between 4cm vs 9cm , 6cm vs 9cm and 7cm vs 9cm in 2D with p values of 0.041, 0.02 and 0.073. However, there was no difference (within group analysis) in 3D imaging.

4.2.3 Distance comparison

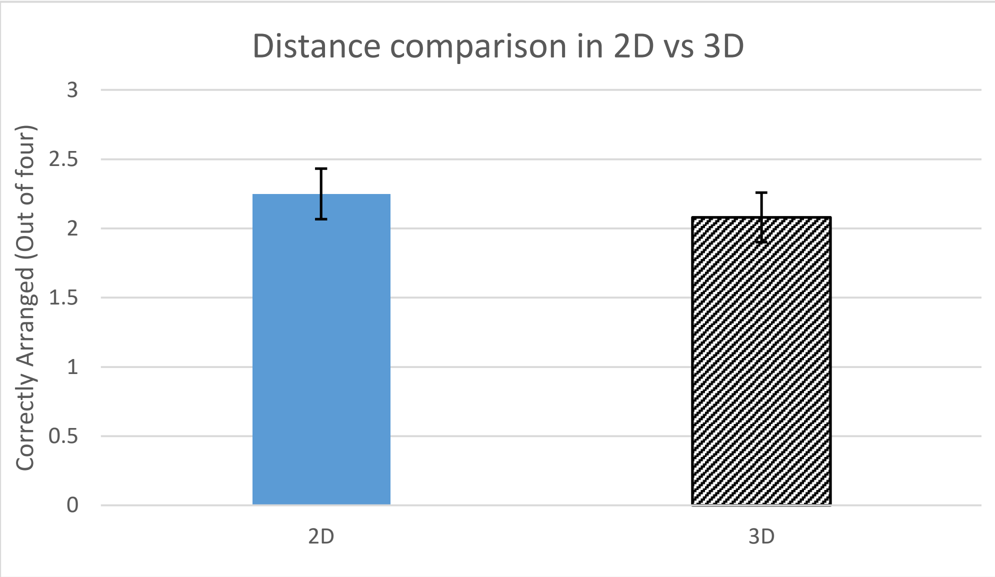


Figure 18: Histogram of distance comparison in 2D vs 3D

There was no difference in distance comparison between the 2D and 3D imaging.

4.3 Area

4.3.1 Square measurement

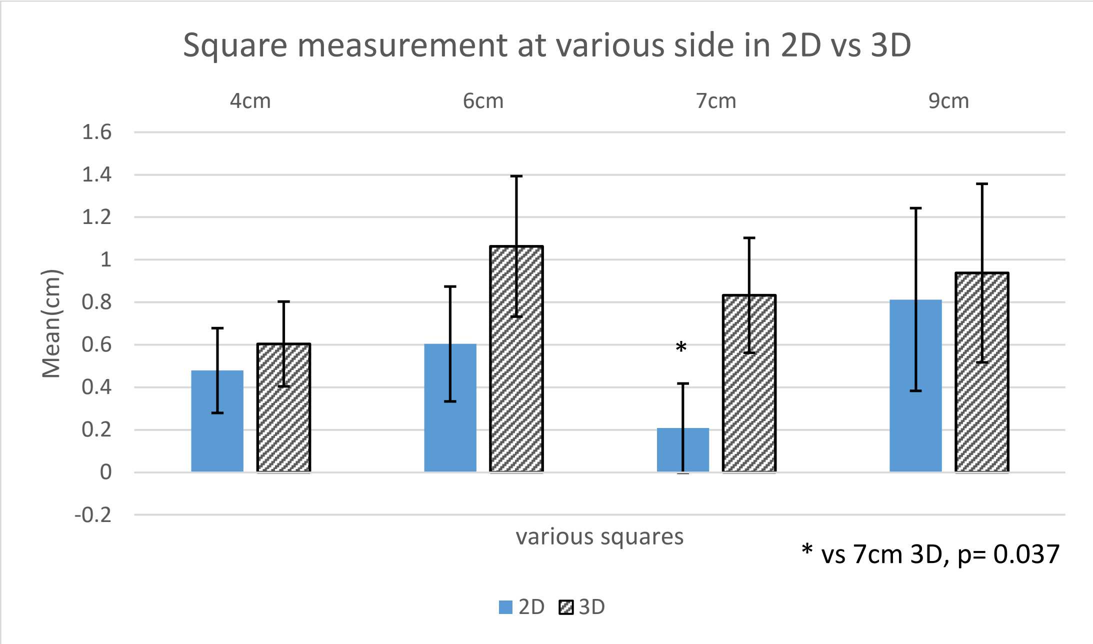


Figure 19: Histogram of square measurement at various side in 2D vs 3D

The 2D group performed significantly better at measuring the 7cm square when compared to 3D group with p value of 0.037. There was no significant statistical difference between and within group for other squares.

4.3.2 Circle measurement

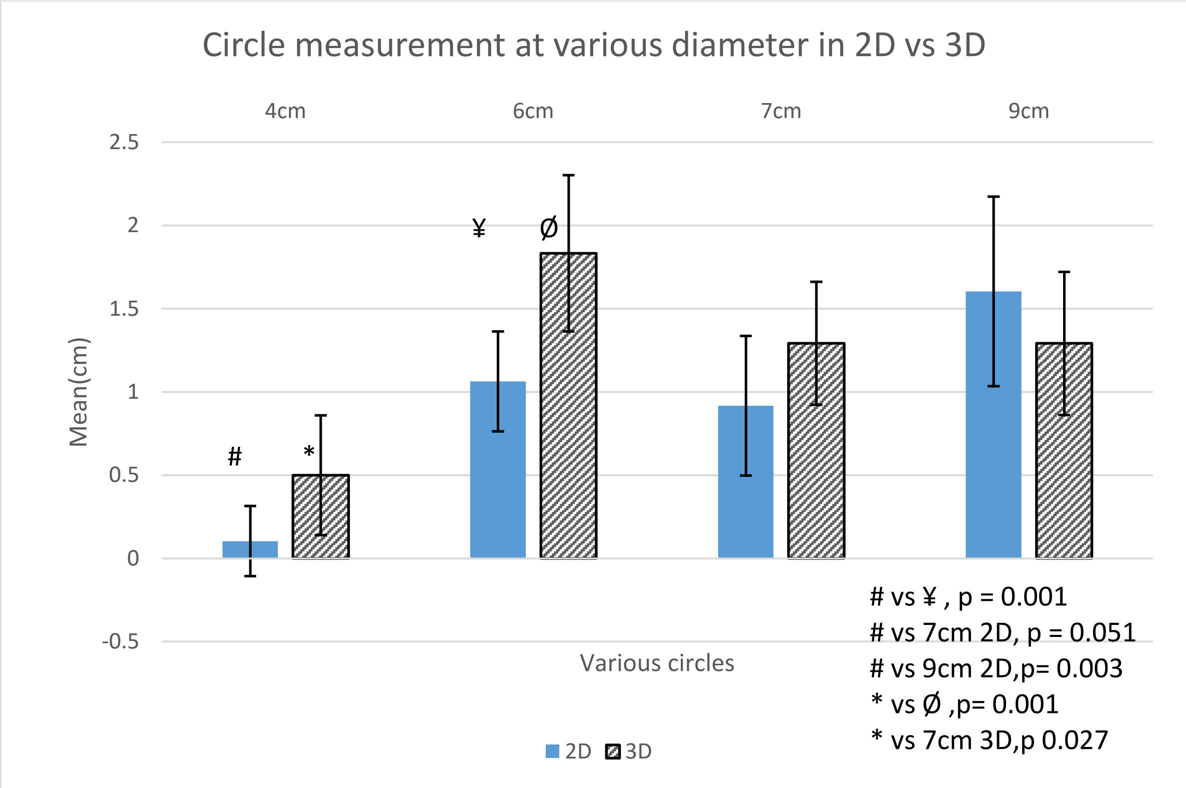


Figure 20: Histogram of circle measurement at various diameters in 2D vs 3D

The most accurate diameter for circle measurement was 4cm. Generally, circle measurement showed a trend of overestimation with the increase of circle diameters in both surgical imaging. However, there was no significant difference in between the 2D and 3D at any measurement points. For 2D group analysis, there was a significant difference between 4cm vs 6cm (p = 0.001), 4cm vs 7cm (p= 0.051) and 4cm vs 9cm (p = 0.003). For 3D group analysis, there was a significance difference between 4cm vs 6cm (p=0.001) and 4cm vs 7cm (p =0.027).

4.3.3 Square comparison

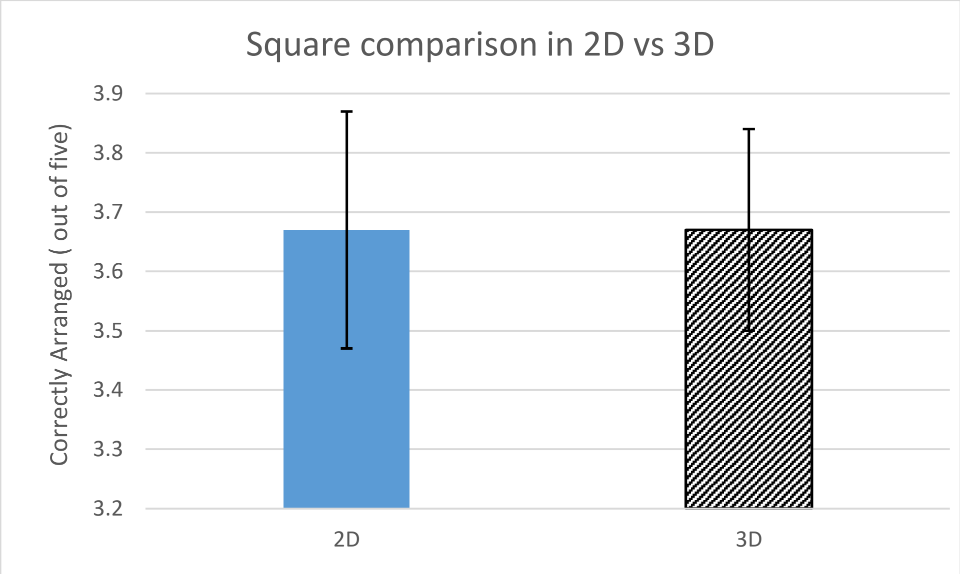


Figure 21: Histogram of square comparison in 2D vs 3D

There was no significant difference in square comparison in 2D and 3D imaging.

4.3.4 Circle comparison

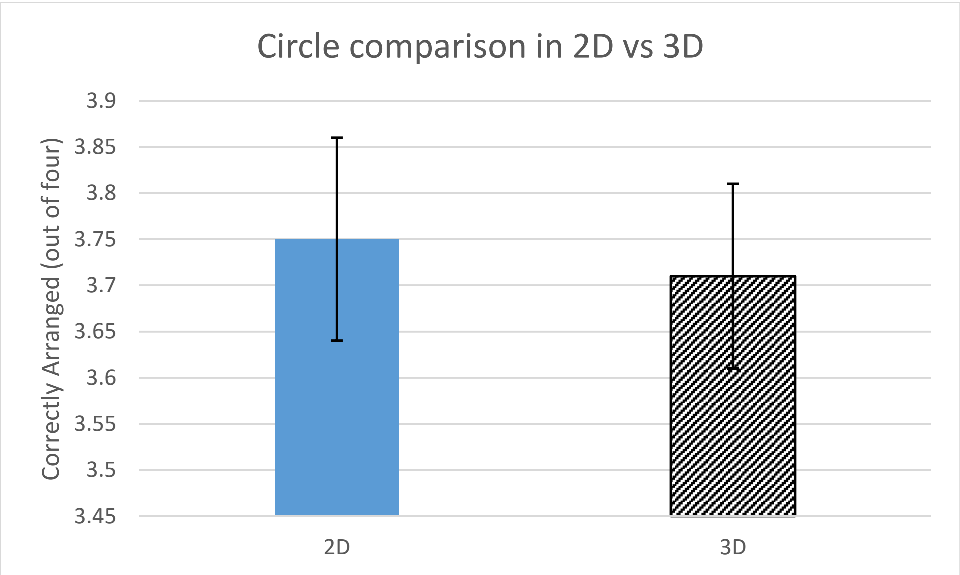


Figure 22: Histogram of circle comparison in 2D vs 3D

There was no significance difference in circle comparison between the 2D and 3D.

4.3.5 Square vs Circle at different values in 2D

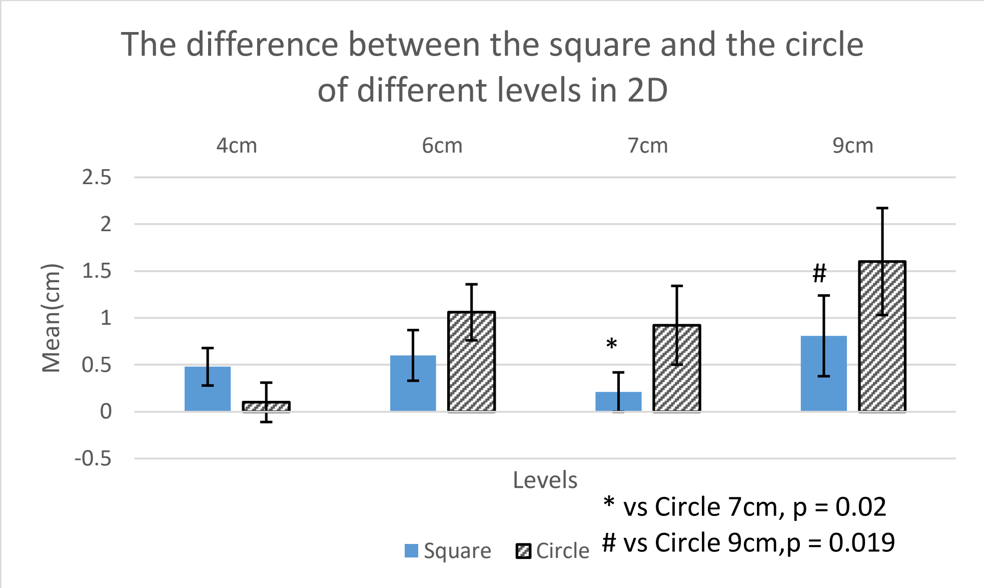


Figure 23: Histogram of the difference between the square and the circle of different levels in 2D

For the analysis between the shapes (square vs circle), the square at 7cm and 9cm showed superiority in 2D imaging with p value of 0.02 and 0.019 respectively.

4.3.6 Square vs Circle at different values in 3D

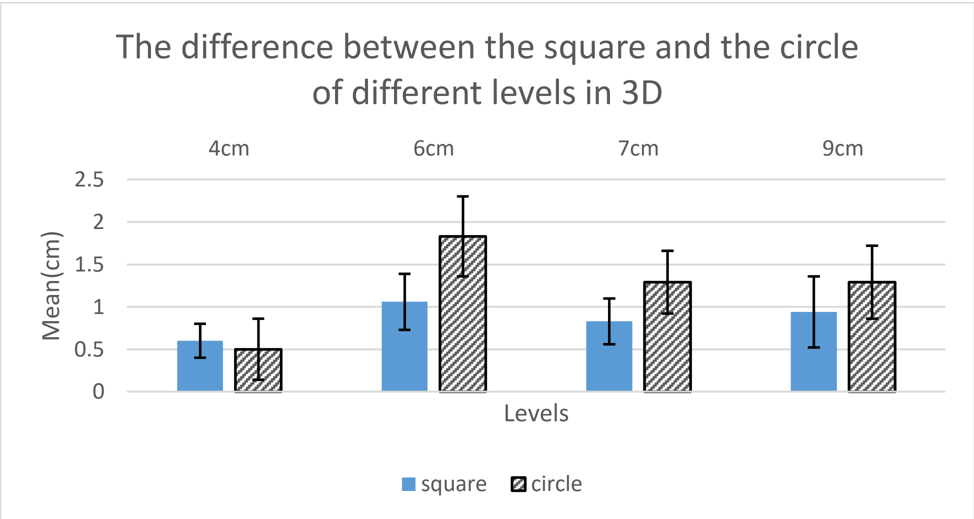


Figure 24: Histogram of the difference between the square and the circle of different levels in 3D

There was no statistically significant difference between the square and the circle at any levels in 3D.

4.4 Angle

4.4.1 Angle creation

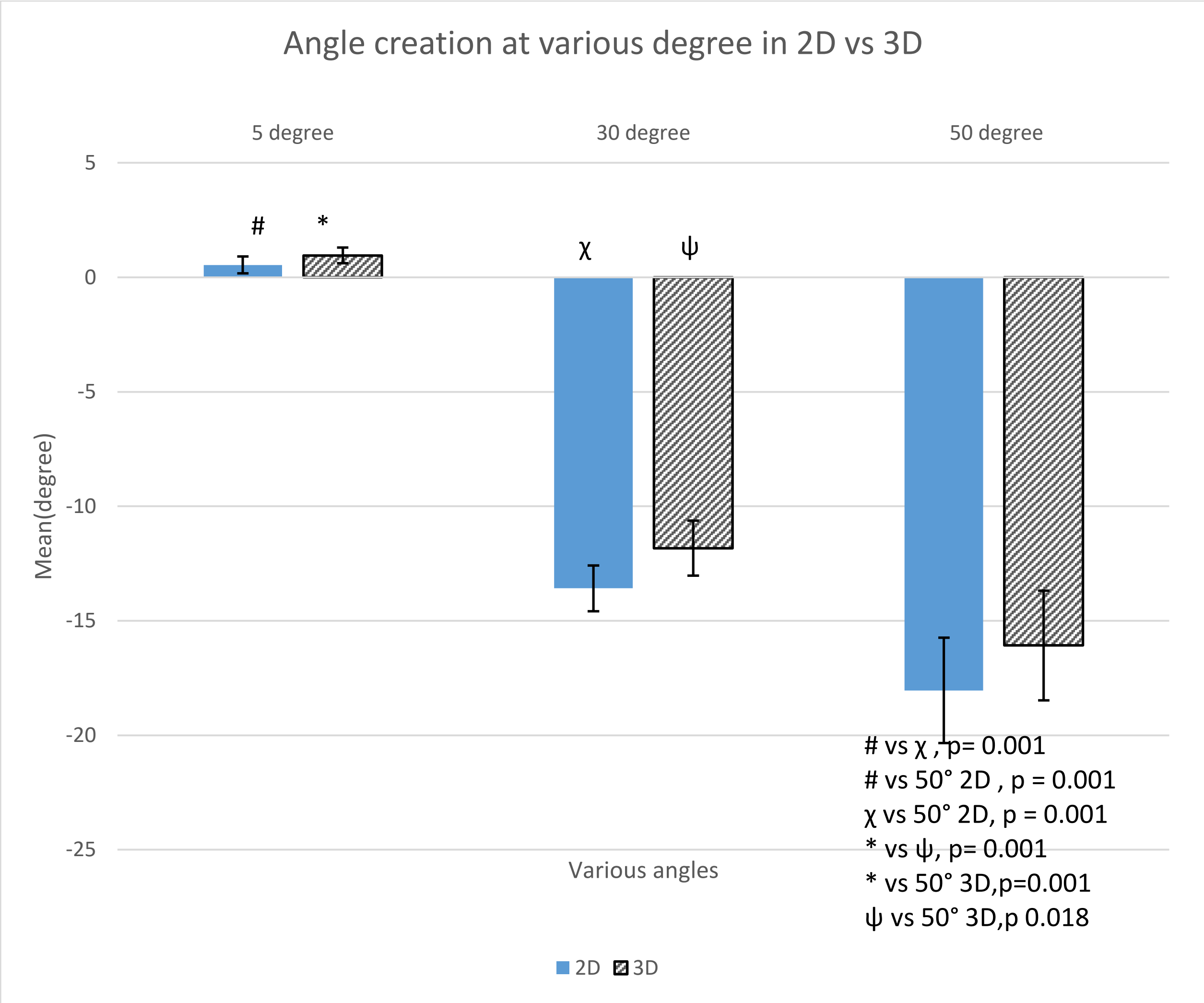


Figure 25: Histogram of angle creation at various degrees in 2D vs 3D

The most accurate degree for angle creation for both 2D and 3D imaging was 5 degrees. In angle creation, there was a small variation (overestimation) at 5 degree for both surgical imaging. However, there was an underestimation for 30 and 50 degrees. This showed that larger the angle, the greater is underestimation of the angle in angle creation in 2D and 3D imaging. There was no statistical significant difference of angle creation at various degrees between the 2D and 3D. For 2D group analysis, there was a difference between 5 degree vs 30 degree (p = 0.001), 5 degree vs 50 degree (p= 0.001) and 30 degree vs 50 degree (p=0.015). For 3D group analysis, there was a difference between 5 degree vs 30 degree (p =0.001), 5 degree vs 50 degree (p= 0.001) and 30 degree vs 50 degree (p=0.018).

4.4.2 Angle measurement

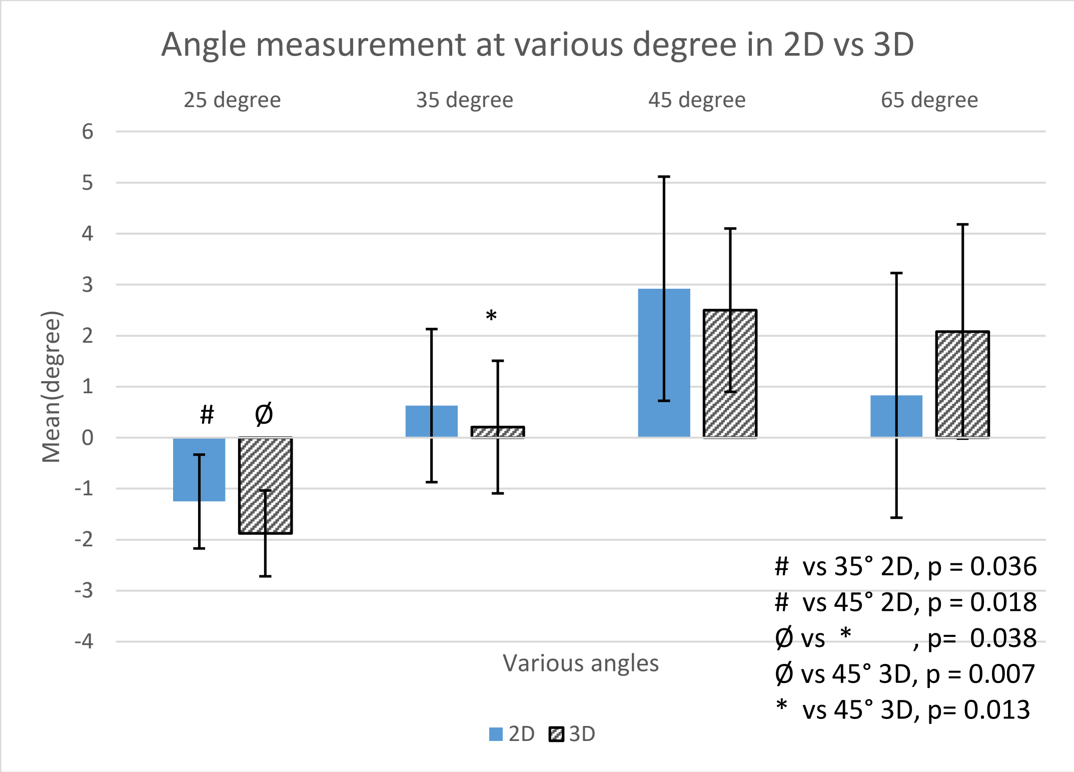


Figure 26: Histogram of angle measurement at various degrees in 2D vs 3D

As the degree increases from 25 onwards, the overestimation increases up to 45. The most accurate angle measurement was at 35 degrees. There was no statistical difference in angle measurement between the 2D and 3D imaging. For 2D group analysis, there was a difference between 25 degree vs 35 degree and 25 degree vs 45 degree(p= 0.036 , 0.018). For 3D group analysis, there was a difference between 25 degree vs 35 degree (p=0.038), 25 degree vs 45 degree (p=0.007). 35 degree vs 45 degree (p=0.013).

4.4.3 Angle comparison

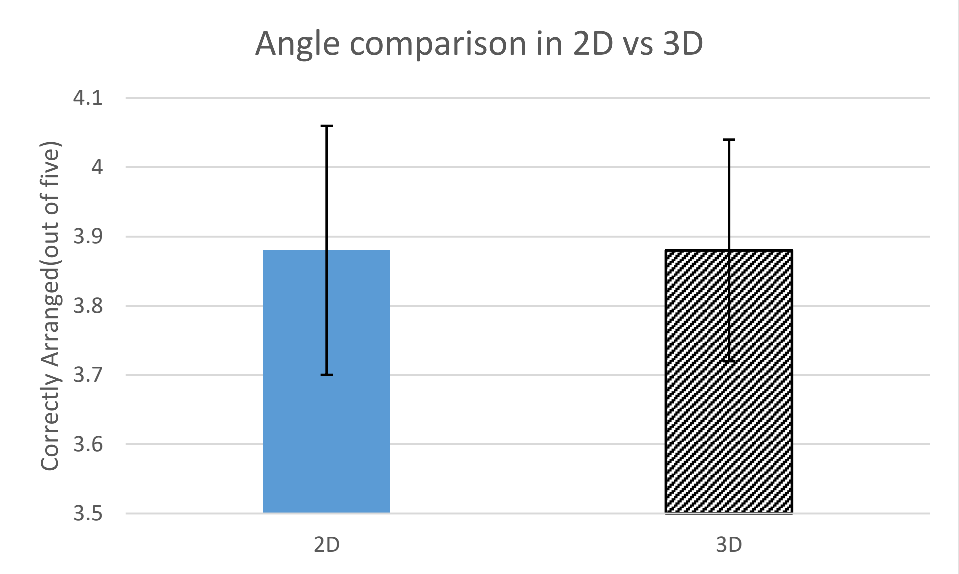


Figure 27: Histogram of angle comparison in 2D vs 3D

There was no statistical significant difference in angle comparison between the 2D and 3D imaging.

4.5 Volume

4.5.1 Volume creation

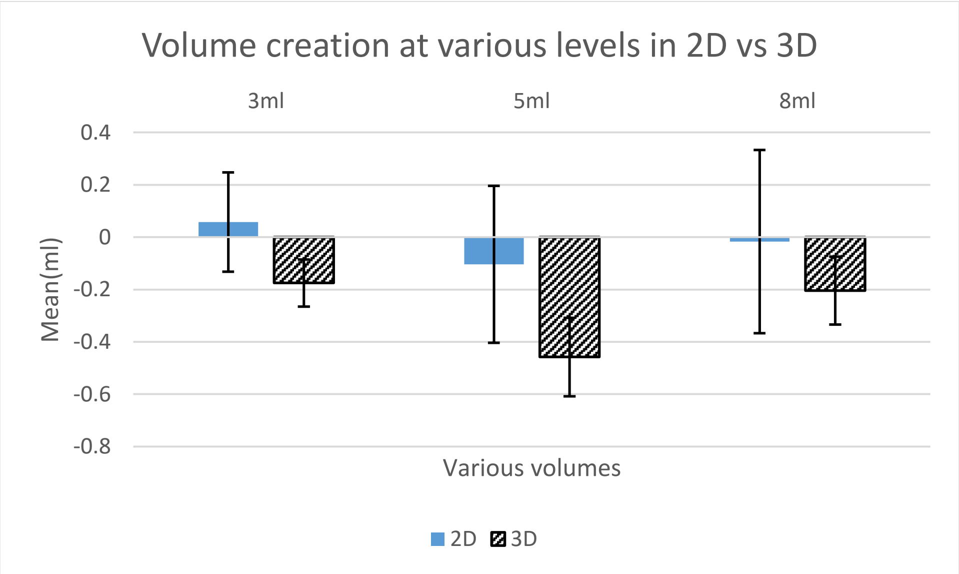


Figure 28: Histogram of volume creation at various sizes in 2D vs 3D

The most accurate volume for volume creation was 3ml. For volume creation, 2D imaging showed more uncertainties with wider confidence interval (SEM) compared with 3D. However, the difference between the 2D and 3D was not statistically significant. There was no difference in 2D and 3D for within group analysis.

4.5.2 Volume measurement

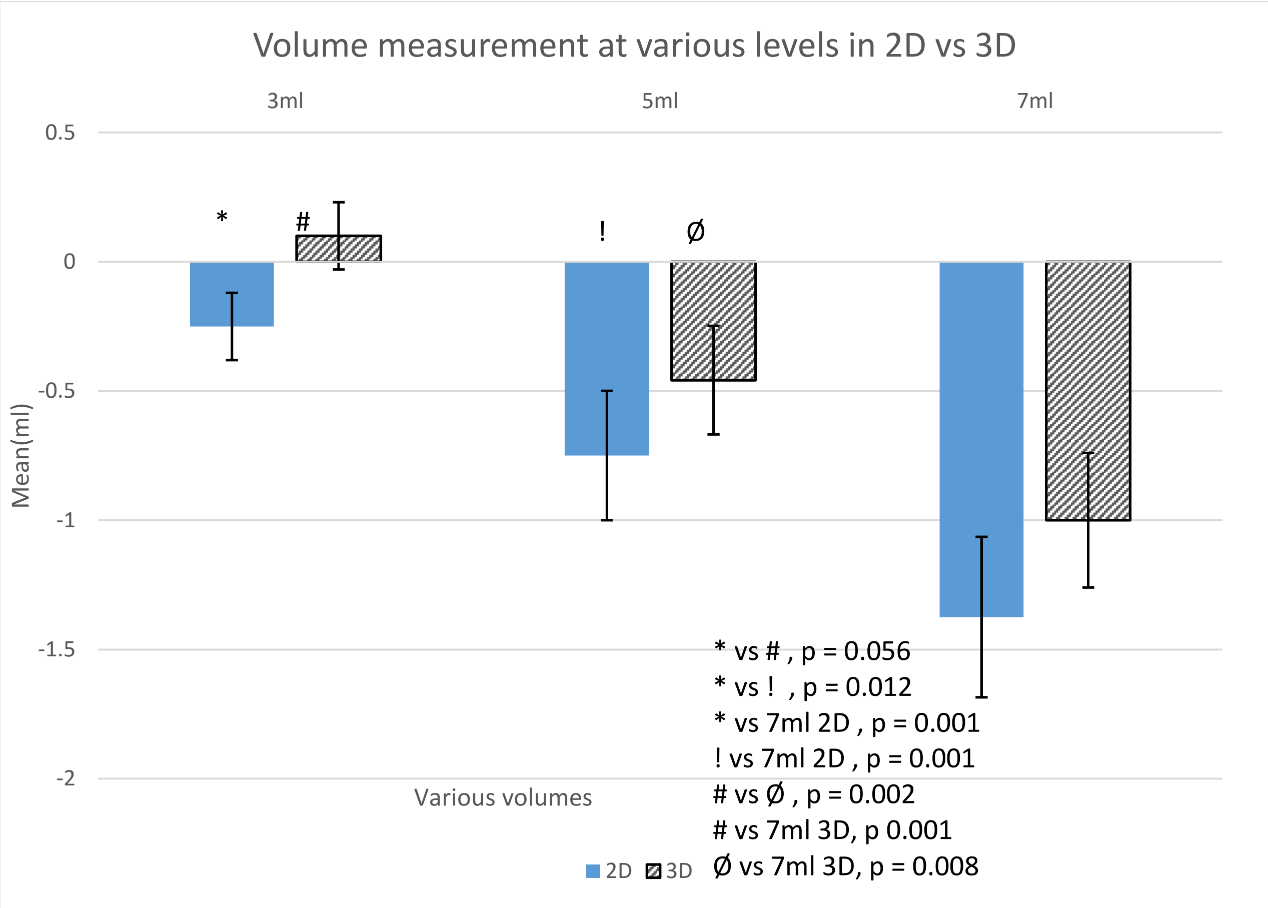


Figure 29: Histogram of volume measurement at various levels in 2D vs 3D

The most accurate volume for volume measurement was 3ml.The trend revealed underestimation of volume measurement with the gradual increase in volume in both imaging with 3D showed more accuracy. There was a statistically significant difference in volume measurement at 3ml with 3D performing better (p value of 0.056). However, there was no difference at 5ml and 7ml between 2D and 3D imaging. For 2D group analysis, there was a statistically significant difference between 3ml vs 5ml (p = 0.012), 3ml vs 7ml (p= 0.001) and 5ml vs 7ml (p=0.001). For 3D group analysis, there was a difference between the 3ml vs 5ml (p =0.002), 3ml vs 7ml (p= 0.001) and 5ml vs 7ml (p= 0.008).

4.5.3 Volume comparison

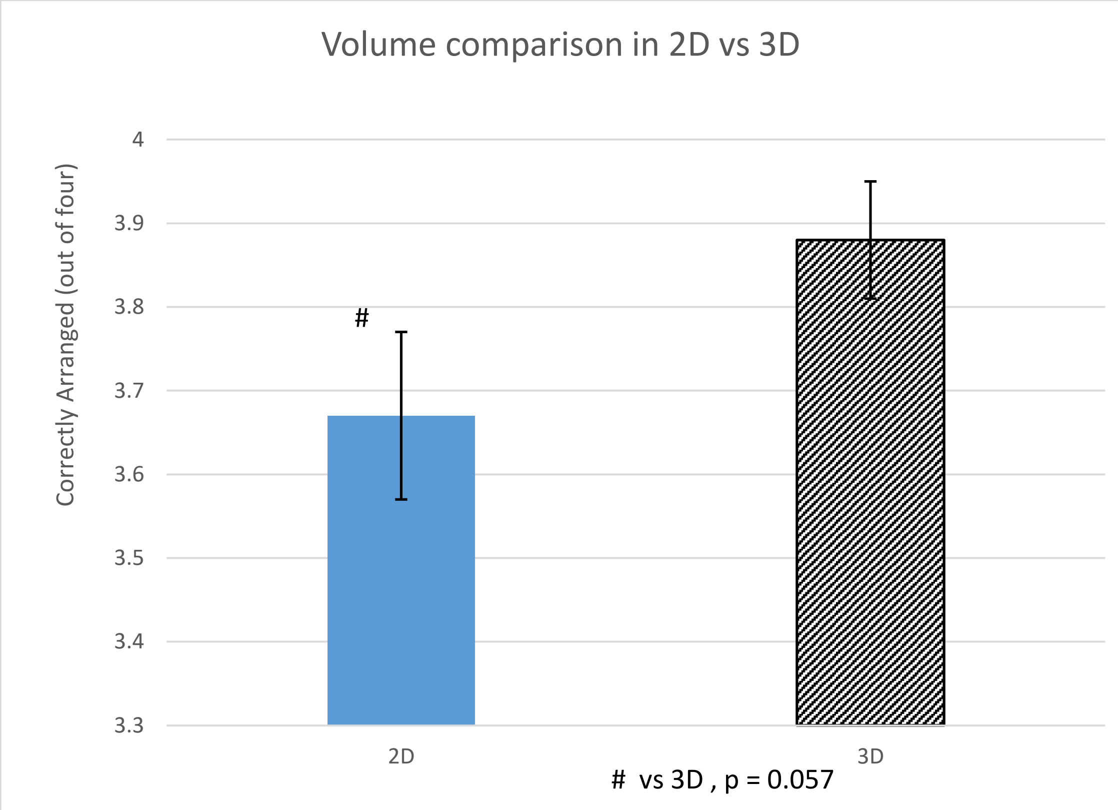


Figure 30: Histogram of volume comparison in 2D vs 3D

There was a statistical significant difference in volume comparison with 3D showing superiority (p=0.057).

4.6 Curvature

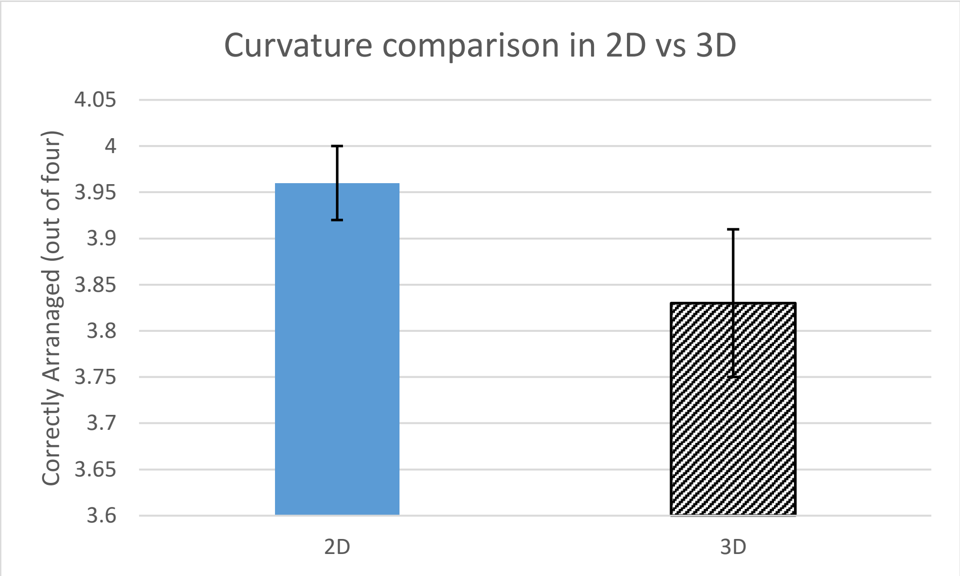


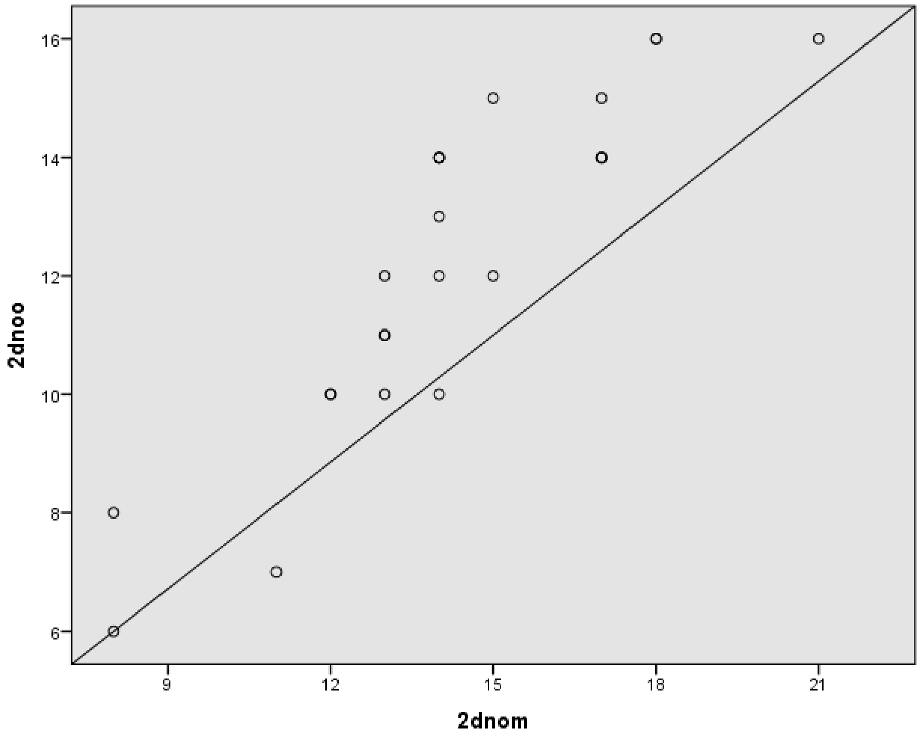
Figure 31: Histogram of curvature comparison in 2D vs 3D

There was no statistically significant difference in curvature comparison in 2D and 3D imaging.

4.7 Spatial coordinates

4.7.1 Correlation between number of movement and number of touched objects in 2D and 3D

Adjusted R^2- 0.79

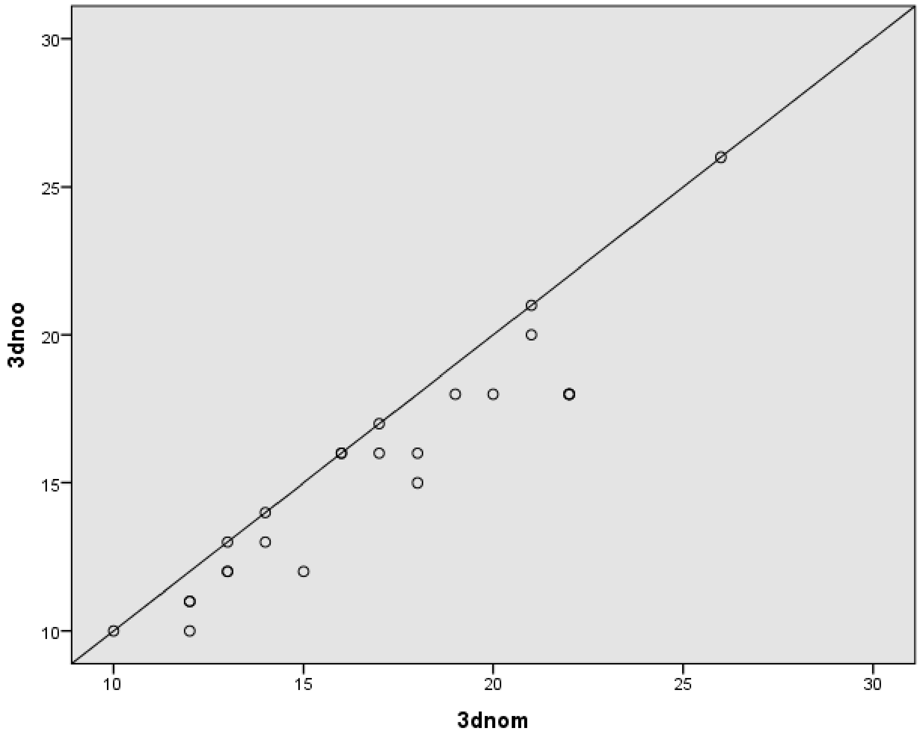


2dnoo- 2D number of objects, 2dnom- 2D number of movement

Figure 32: Scatter plot showing correlation between the number of movement and number of touched objects in 2D

The graphs showed the correlation between number of movement and number of touched objects in 2D with adjusted R^2 of 0.79.

Adjusted R^2- 0.89



3dnoo- 3D number of objects, 3dnom- 3D number of movement

Figure 33: Scatter plot showing correlation between the number of movements and number of touched objects in 3D

The correlation graph showed strong correlation between the number of movements and number of touched objects in 3D with adjusted R^2 of 0.89.

4.7.2 Number of errors, number of movements and object touched in 2D vs 3D

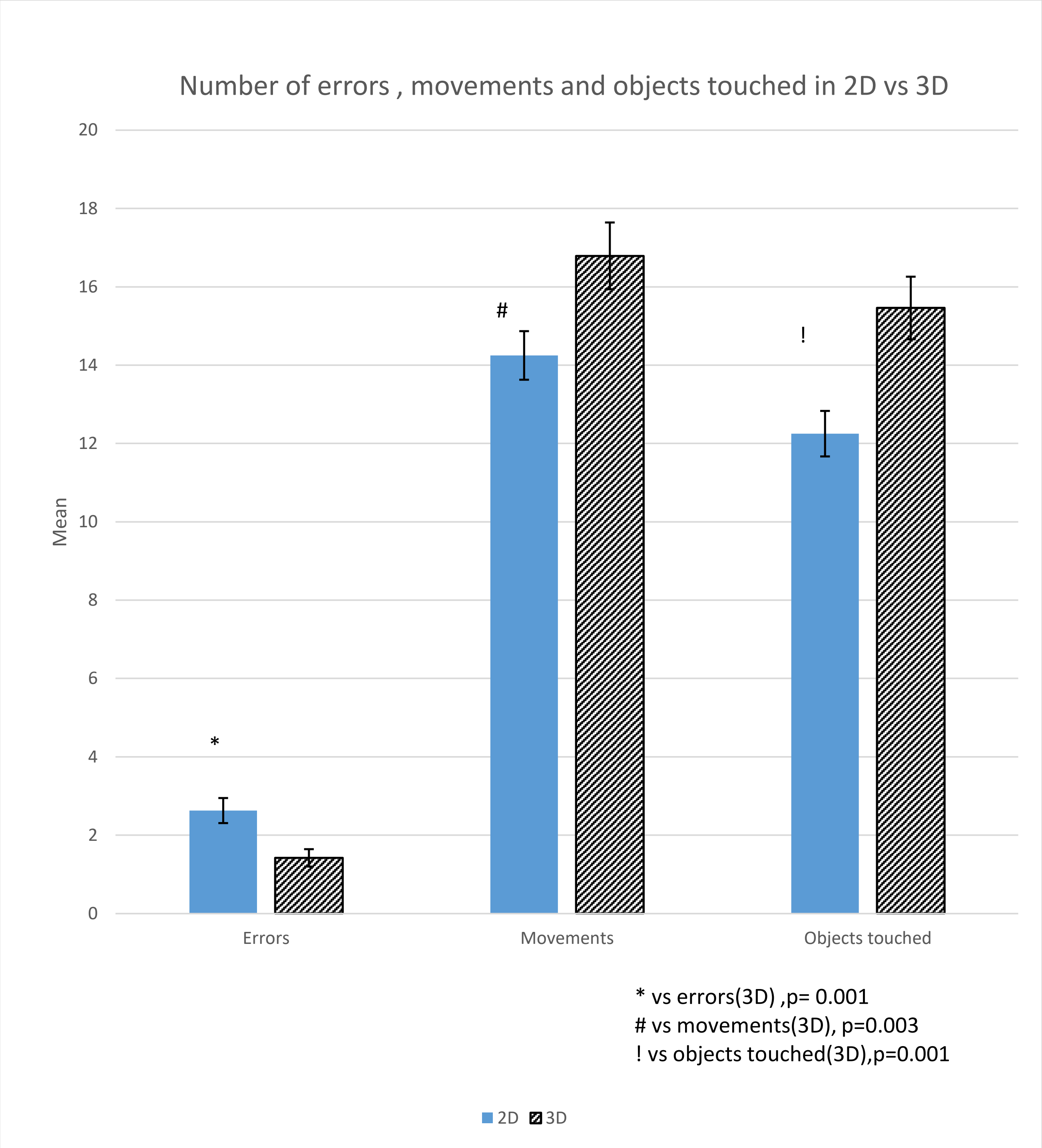


Figure 34: Histogram of number of error, number of movements and objects touched in 2D vs 3D

The Human Reliability Analysis (HRA) showed that number of errors were higher in 2D imaging when compared with 3D and was statistically significant (p=0.001). The number of movements was better at 2D with p value of 0.003. For number of objects touched within a minute, the 3D showed superiority with p value of 0.001.

4.7.3 Type of errors in 2D vs 3D in spatial coordinates test

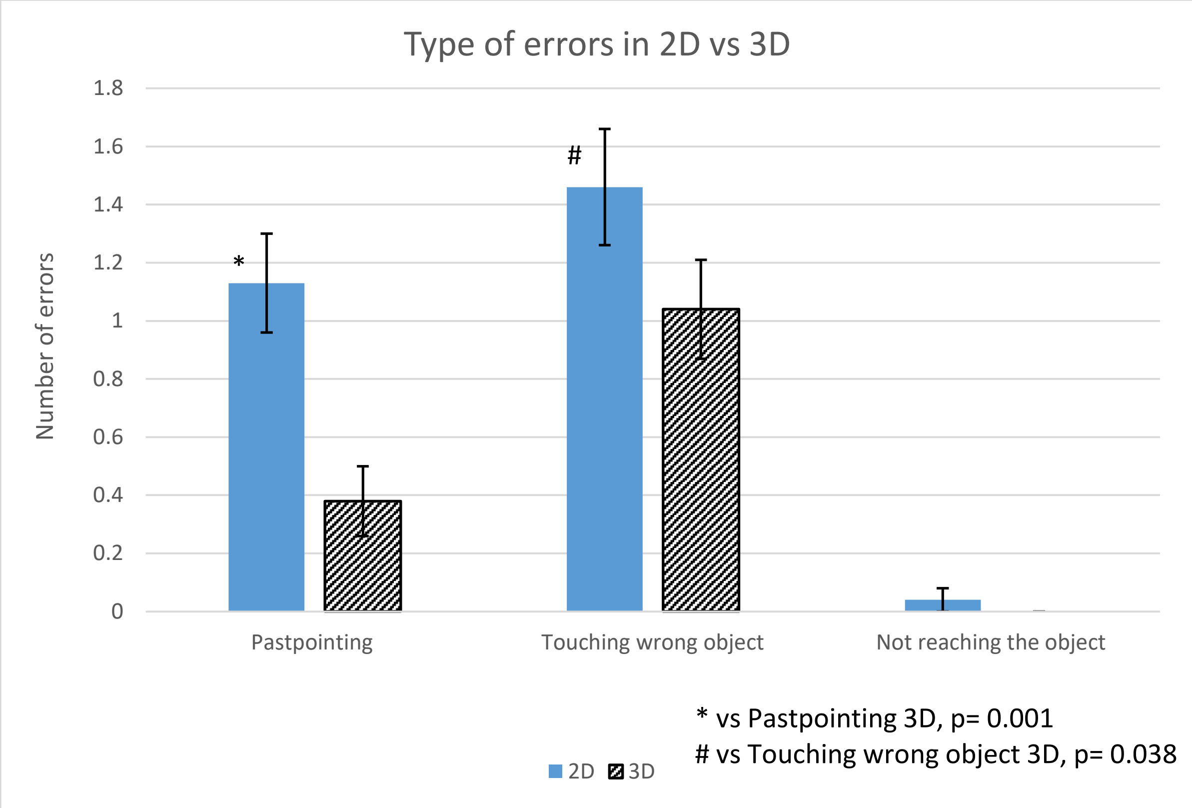


Figure 35: Histogram of type of errors in 2D vs 3D

For the type of errors, the pastpointing (p=0.001) and touching wrong objects (p=0.038) were statistically significant and higher in 2D. The error of not reaching the object was not statistically significant.

4.7.4 Error probability

Error probability(NOE/NOM) x 100	**Percentage**
2D Imaging	18.4
3D Imaging	8.4

Table 9: Error probability

The error probability was derived from the ratio of number of errors to number of movements. The error probability was multiplied with 100 to derive the error percentage. Error probability calculation revealed that a 10 percent higher probability of committing errors in 2D compared to 3D.

4.8 Visual symptoms

4.8.1 Eye deviation after 2D and after 3D, before 2D and after 2D, before 3D and after 3D.

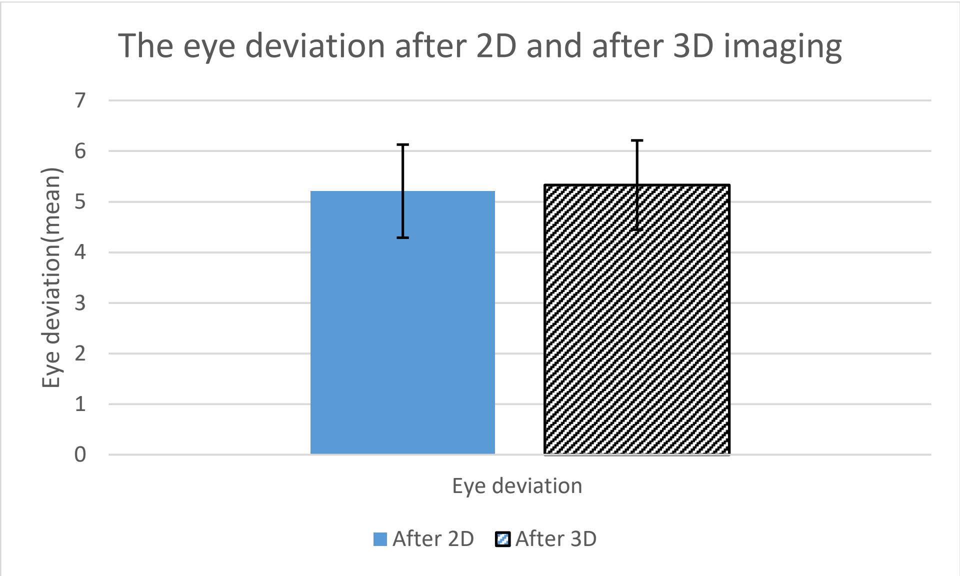


Figure 36: Histogram of the eye deviation after 2D and after 3D imaging

There was no statistically significant difference in eye deviation after the 2D and 3D imaging.

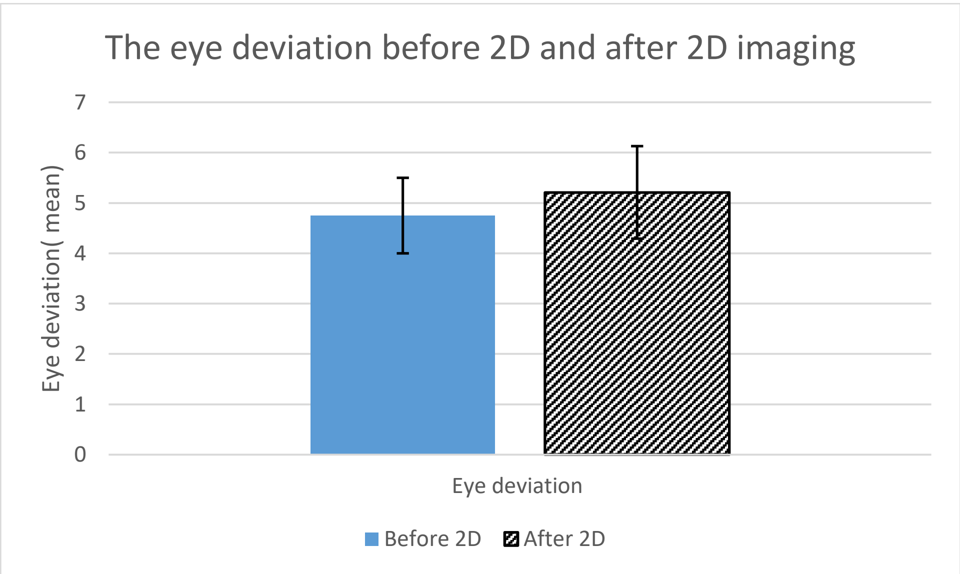


Figure 37: Histogram of the eye deviation before 2D and after 2D imaging

There was no statistically significant difference in eye deviation before 2D and after 2D imaging.

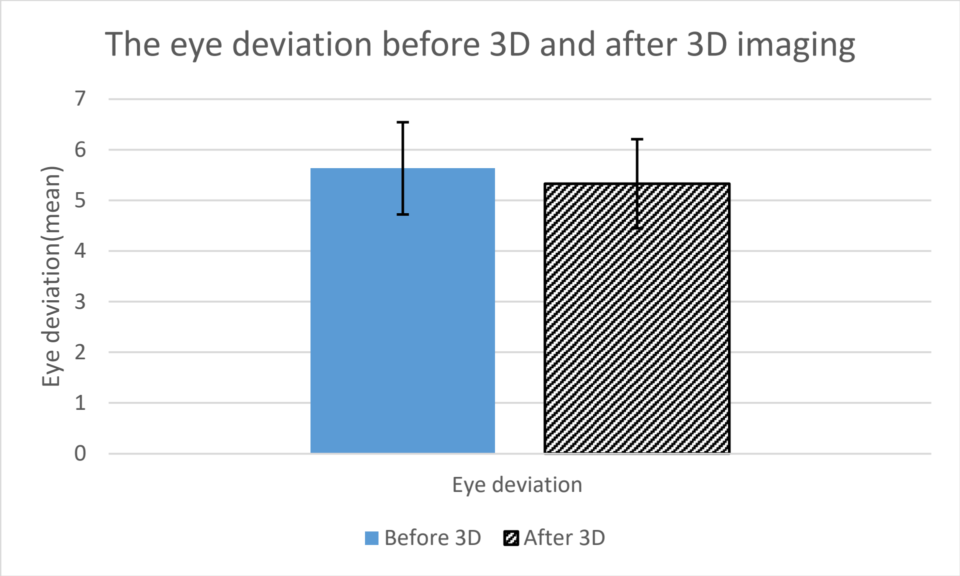


Figure 38: Histogram of the eye deviation before 3D and after 3D imaging

There was no statistically significant difference in eye deviation before 3D and after 3D imaging.

4.8.2 Visual symptoms after 2D and after 3D, before 2D and after 2D and before 3D and after 3D

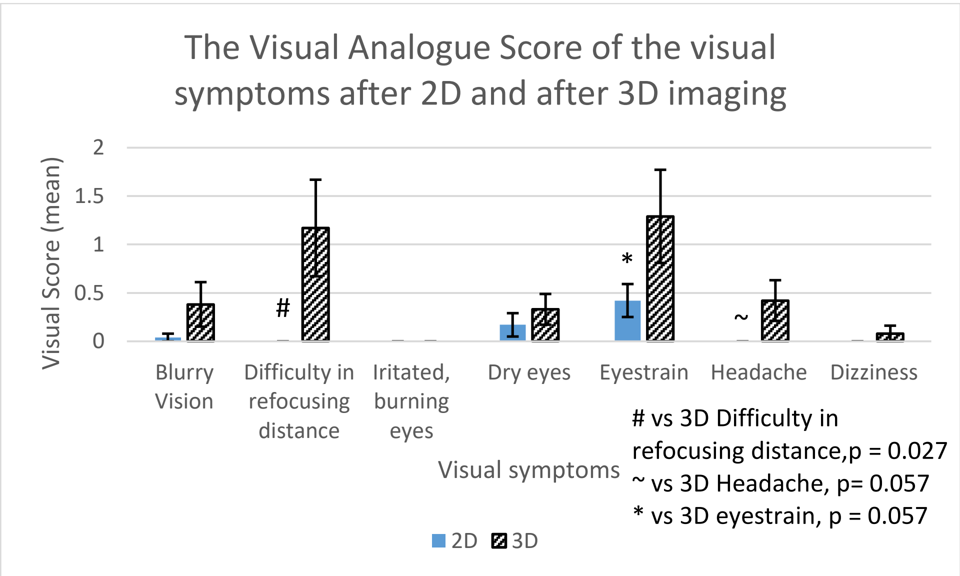


Figure 39: Histogram of the visual analogue score of the visual symptoms after 2D and after 3D imaging

For visual symptoms between the 2D and 3D imaging, difficulty in refocusing from one distance to another, headache and eyestrain were significant in 3D with p values of 0.027. 0.057 and 0.057.

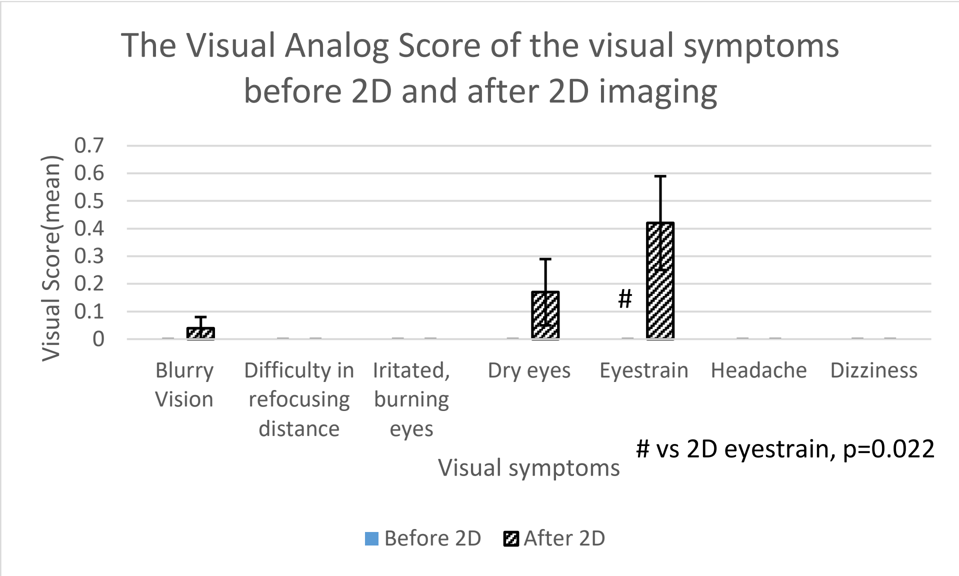


Figure 40: Histogram of the visual analogue score of the visual symptoms before 2D and after 2D imaging

For eye symptoms in 2D imaging alone (before and after 2D imaging), visual analogue score revealed that eye strain was statistically significant in 2D imaging (p=0.022).

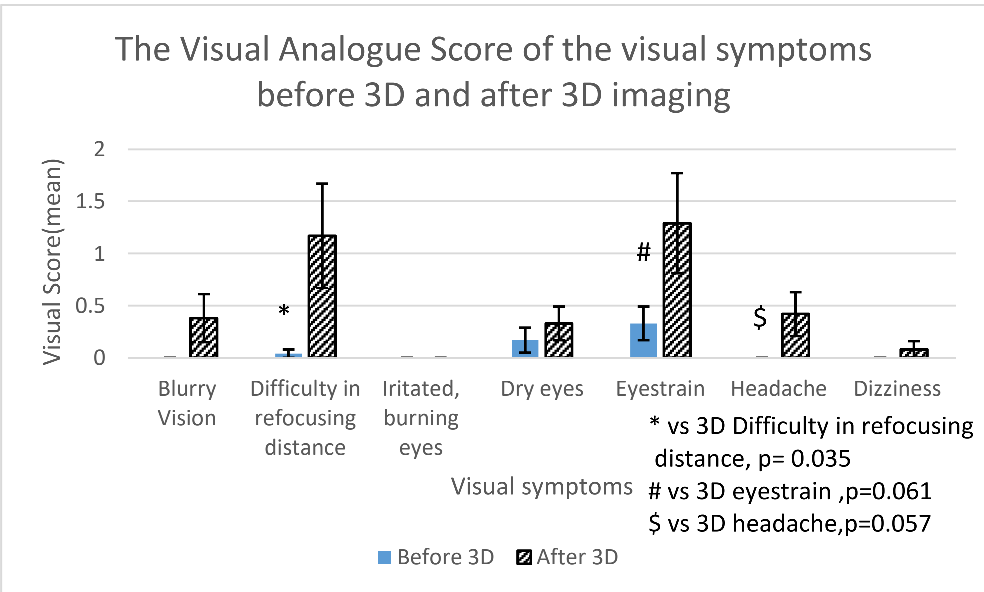


Figure 41: Histogram of the visual analogue score of the visual symptoms before 3D and after 3D imaging

For 3D imaging alone (before and after 3D imaging), the difficulty in refocusing in one distance from another was statistically significant (p=0.035). The eye strain and headache were marginally significant with p values of 0.061 and 0.057 respectively.

4.8.3 The effect of eye exercise in visual symptoms in 3D

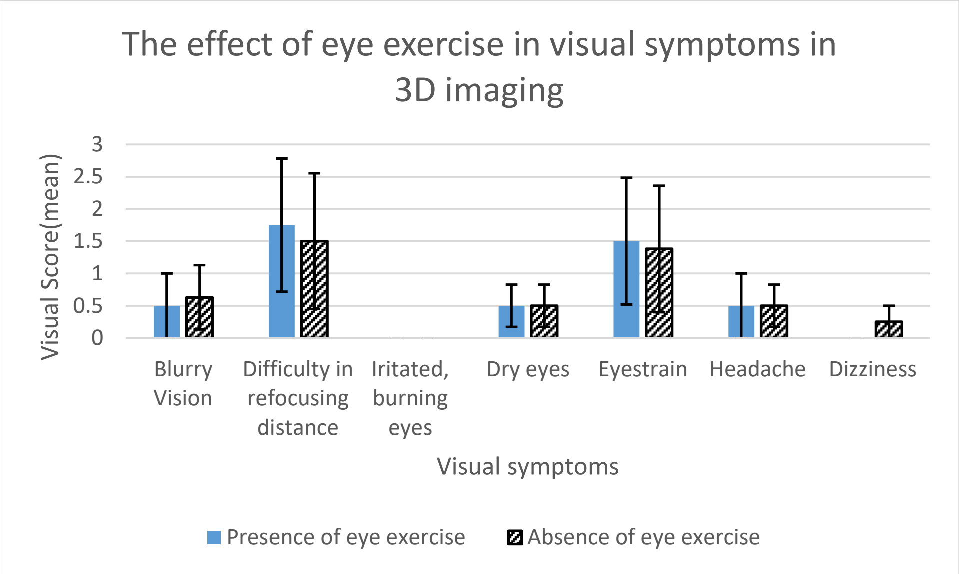


Figure 42: Histogram of the effect of eye exercise in visual symptoms in 3D imaging

The visual symptoms were scored for the 3D group with and without eye exercises and independent t-test was used to detect any difference. The results showed that there was no significant visual symptom improvement in 3D with eye exercises.

4.8.4 The effect of eye exercise on eye deviation in 3D

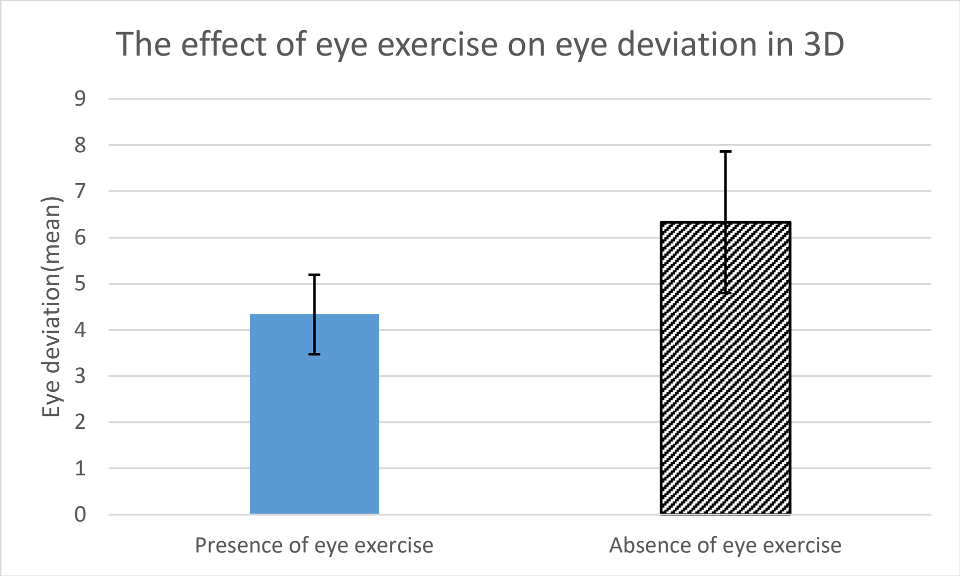


Figure 43: Histogram of the effect of eye exercise on eye deviation in 3D

Eye exercise produced less eye deviation in 3D with p value of close to statistical significance (p= 0.052).

CHAPTER 5

Chapter 5 Discussion

5.0 Generic components

We have shown that 3D imaging improves the task performance in detecting change in volume and in spatial coordinates when compared to 2D. There was no statistical difference in detecting changes in the area, angle, distance and curvature between 2D and 3D surgical imaging.

This is the first attempt studying the individual visual components of a laparoscopic image in 2D and 3D laparoscopy. The task performance and surgical errors have previously been assessed by using composite tests called the fundamentals of laparoscopic modules (peg transfer, precision cutting, ligating loop, extra-corporeal knotting and intra-corporeal knotting) (Tanagho 2012). Unlike the methods used in our study, these tests consist of interplay of various dimensions and are not testing any aspect in isolation. For example, peg transfer itself is a complex task and build up from many small subtasks e.g. holding the peg, transferring the peg, releasing the peg.

Many studies have shown that 3D laparoscopy improves the task performance when compared to 2D (Sorensen et al. 2015). Learning of laparoscopic skills involves hand–eye coordination, manual dexterity and visual spatial coordination. Unlike open surgery, in the conventional 2D laparoscopic image, the surgeon requires to interpret the image into a 3D imagery. This is made more difficult by a narrow working space, magnification and pressure of acquiring new skills. In 3D laparoscopy, the surgeon adjusts artificial 3D imagery to a self-constructed 3D view. The 3D laparoscopic image may require less mental processing than a 2D for constructing a realistic image in a surgeon's mind. This could explain partly why 3D imaging improves surgical task performance.

There are a number of basic physical characteristic of the shape of any image, which consists of distance, area, angle, curvature and volume. While the distance and curvature are one-dimensional, the area and angle are two-dimensional, and volume is three-dimensional in character. A further factor is the position of the shape or object in space in relation to the surrounding structures, i.e. spatial coordinates.

A surgical task is generally an interplay of three basic dimensions of distance, force and time. The entity of distance is further subdivided into the following components: angle, area, volume and curvature. In the laparoscopic surgery, the notion distance is equivalent to depth perception when the line of view is in parallel to the distance to be measured. Depth perception is the subcategory of the distance perception. Distance perception is the skill to judge the distance of objects and the spatial relationship of objects at different distances. Visual cues are perceived as important in distance perception. Angle is defined as space or degree created by two intersecting lines when these lines meet at one point. Area of a shape i.e. square or circle is a measure of the 2 dimensional space that it covers and curvature on the other hand is derived from circle and is the product of reciprocal of a radius of a circle. Volume is measure of the amount of 3D space that an object occupies. And how this each and individual components change in 2D and 3D imaging independently is the question that we attempted to answer in this thesis.

There are other components that may play a role in distance perception but we did not include in our experiment i.e. shadow and texture gradient. Study by Hanna et al (2002) has showed that there was significant improvement in simple 2D laparoscopic task performance when shadow was introduced in the operative field. Another study by Mishra et al (2004) also demonstrated the net advantage of the shadow inducing system on task performance and identified the optimal position and contrast for casting shadows in 2D system. Lee CS et al (2013) studied the effect of dynamic shadowing in 2D and 3D imaging in a laparoscopic trainer. They found that dynamic shadow in 2D imaging was better with reduced mean execution time and less errors in laparoscopic tasks than 3D display.

The texture is also found to be a visual cue in estimating distance. For example, in a close view of a wall, we can see the texture of wall clearer. As the wall moves farther away, the texture become finer and smoother (Gibson 1950). In surgery, inflamed tissue have rougher appearance compared to normal and healthy tissue and may function as an important cue in assessing the distance of the inflamed organ in relation to the surrounding environment.

5.1 Methods

The generic components in this study were evaluated via three distinct methods independently- creation, measurement and comparison. The difference between the creation and measurement may be subtle (see below) but comparison itself stands as a separate entity. Comparison was made feasible by comparing several preset dimensions of the same visual component. Comparison tests were relatively straightforward and did not require much mental effort as presence of visual cues in surrounding environment help substantially. When we analyse how we perceive an action or task, we need to understand the concept of spatial ability. Spatial ability is defined as a set of skills of creating, transforming and recalling symbolic, non- linguistic information (Alias, Maizam 2002). One of the important factor that influence spatial ability is spatial orientation which is the understanding of the comprehension of arrangement of elements within a visual stimulus and the capacity to remain unconfused by the changing orientation (McGee 1979, Strong, S 2002). The spatial orientation was important in all the three investigated methods in our study but may be more pronounced in comparison test.

Measurement and comparison tasks are required prior to the task of creation. We believe the brain works in sequence of logical steps for the task of creation, automatically implementing a thought process. Firstly, brain needs to compare and measure an object with the aid of external cues. The comparison skill uses memory, spatial ability and information from previous experiences as well as presence of visual cues in the environment. On the contrary, measurement skill is dependent more on memories and recalling process.

There are many examples that may demonstrate that the measurement and comparison skills are the prerequisite requirements for any creation task. Let's take opening door as an example. When a person is asked to open a door, that person needs to make certain comparisons initially with visual cues in relation to the door's surrounding environment as well as comparison from the memory and past experiences to come up with the best guess of measurements for the door's physical dimension, as well as magnitude and direction of force required to open the door. These steps are implemented in brain to produce the act of creation. However the task of comparison and measurement do not occur separately. There is a loop of re-evaluating the measurements through continuous comparison process. There are many surgical examples where this process are implemented, for example in usage of stapler device in laparoscopic surgery. When the surgeon insert the stapler limbs into enterotomy , he has to compare and measure various cues in surgical field i.e. length of bowel and stapler limb , size of enterotomy, direction of stapler limbs and recalling previous similar experiences before inserting the limbs and firing the stapler.

We have proposed a chart to depict the mental process for task of creation(task execution) (Figure 44). It is our view that these steps occur in continuous in a loop, therefore we are constantly improving on our comparing and measuring abilities for task of creation and increasing our memory strength (cognitive capacity). We believe that this model may explain the fundamentals behind the Fitts and Posner model of skills acquisition (Figure 45) which is centered on three stages i.e. cognitive, associative and autonomous stages (Fitts, Posner 1967). We need to bear in mind, there always be a presence of confounding factors in each level i.e. poor attention span, lethargy and multitasking therefore interfering in the comparison and measurement skills which will affect the task creation or execution. Although in this discussion measurement task was grouped together with comparison task and differentiated from creation task, all the three methods in this experiment were performed independently.

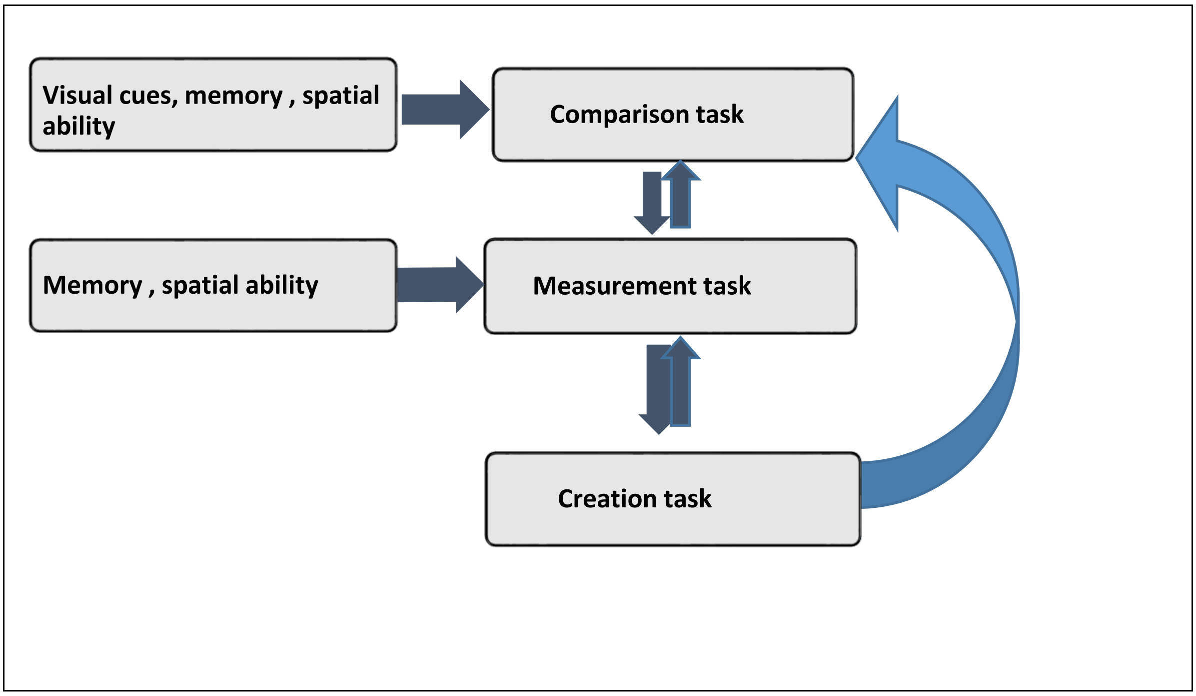


Figure 44 : A proposed chart of mental process in task execution

Figure 45: Fitts and Posner model of skills acquisition

5.2 Results

For the components study, there was no statistical difference in the distance, angle and curvature in 2D and 3D surgical imaging. The most accurate level for distance creation was 2cm and distance measurement was 4cm. It appears that as the distance gets bigger, so is the margin of error. This has clinical relevance as the surgeon may encounter scenarios where he needs to estimate longer length of an organ, for example, in small bowel enterotomy. Thus, one need to bear in mind that larger the length of the segment, wider is the error margin.

Distance creation showed the trend of underestimation for both 2D and 3D imaging and distance measurement revealed trend of overestimation for both 2D and 3D imaging. This is relevant in clinical practice as this under or overestimation may cause surgical errors, complications and eventual death. For example, in bariatric surgery, overestimating small bowel limb may contribute to malabsorption and nutritional deficiencies. The longitudinal incision of cardio-esophageal junction during Heller's cardiomyotomy is also another scenario where distance measurement should be near precise to avoid unwanted complications. This may increase patient's mortality and morbidity. The ability to measure distance is essential as the surgeon has to estimate the distance of the crucial structures in the working area, for example, the positioning of the tip of the needle into the tissue during the continuous suture to create equal distance sutures.

For the area (square) measurement, there was a statistical difference only for 7cm in 2D with p value of 0.037. There was no effect of shapes (square vs circle) on 3D imaging except for square measurement at 7cm and 9cm which revealed superiority in 2D. Most important clinically, circle measurement did not reveal any statistically significant changes in 3D except that there is a trend of overestimation with the increase of circle diameters in both surgical imaging. This is vital information as circle, as per shape has more practical implication than square component. For example, as in the case of Nissen 360 degrees fundoplication where the fundus of stomach brought around the cardio- esophageal junction resulting in a circular like shape, bearing in mind that there is higher tendency that one may create an extreme floppy wrap due to overestimation. In practical surgery, this may be avoidable using a bougie depending on surgeon preference. In addition, estimating the diameter of a circle is a very important visual cue for appreciating the area, for example in laparoscopic mesh placement in abdominal hernias. We have shown that 3D has no impact on circle measurement.

The most accurate degree for angle creation was 5 degree. And larger the angle, greater is the underestimation of the angle creation in both imaging. For angle measurement, the perfect degree was 35 and this is surprising as theoretically the degree of 45 was assumed to be easier to measure. It is difficult to find a plausible reason for this finding. But most probably, it is due to the placement of the angle in the card board in the experiment (spatial orientation). The angle was placed with angle point facing upwards instead of conventional sidewards. This position would have caused difficulty for the participants to mentally rotate, compare, visualize, and measure the size of angle.

Appreciation of angle component is vital in surgical field, for example, as in the placement of suture needle to a desired angle to needle holder and adjustment of the angle of the roticulating laparoscopic stapler. The other aspect that need to be borne in mind is, there are many imaginary angles that can be created while working in a confined and narrow space. For example, in case of pelvic surgery, pelvic angulation per se plays an important role and in fact the main reason for the complexity of pelvic surgery. The traction of the pelvic organs in relation to the angulated pelvis create more significant imaginary angles that work as cues for depth perception. The fact that greater the angle is, more is underestimation in angle creation may give a tip or cue for surgeons operating in this anatomically significant space.

The volume was expected to deliver superior result in 3D theoretically but the results showed mixed results with volume measurement only at 3ml and volume comparison revealed superiority in 3D. There was no statistical difference between 2D and 3D for other volume. The most accurate volume for both volume creation and measurement was 3ml. Both volume creation and measurement revealed trend of underestimation with the gradual increase in volume in both imaging. This is important especially in bariatric surgery where the skills of gastric pouch creation and creation of sleeve gastrectomy form the fundamental steps of the bariatric surgery, integrating skill of estimating volume by the trained surgeon. One has to understand that the created larger gastric pouch may be smaller in reality due to underestimation and it may give rise to complications.

The curvature of a circle is the inverse of its radius. Small radius creates sharp curve, and large radius will create a smoother curve. Most anatomical structures have a curvature. Appreciating the curvature of the structures is important in laparoscopic surgery. Grasping the fundus of the gall bladder at the appropriate place for retraction during the dissection of Calot’s triangle in laparoscopic cholecystectomy is a good example in appreciating the importance of curvature. In our study, 3D imaging does not provide any advantage over 2D in curvature.

In this study when we observed the overall results of the creation and measurement test across all the generic components except spatial coordinate, there was an obvious trend. The creation test generated trend of underestimation while the measurement test showed trend of overestimation except for the volume measurement. It is difficult to explain this findings and may need further study.

Depth perception in our study was assessed with spatial coordinates test. Spatial coordinates experiment was conducted to compare 2D to 3D in locating the position of objects in space. The previous experiments (distance, curvature, angle, area and volume) studied the characters of objects itself; the spatial coordinates experiment tested the ability to judge the location of the object in relation to the surrounding environment. The endpoint for spatial coordinate test were number of errors and the number of movements. Detecting the ability of touching objects were tested by detecting errors in touching the wrong objects, pastpointing and not reaching the object. The results showed that 3D images detect depth perception better than 2D.

The spatial coordinate test that was used in this study was a simple and straightforward study. Multiple objects were tied with strings and suspended from the roof of pelvic trainer. All the objects were arranged in different coordinate in such a way that the object would be touched laparoscopically without hitting other objects. This test was not validated as the validity study itself was a major undertaking. Nevertheless, in retrospect this spatial coordinate study was mere expansion of simple coordinates which was derived from geometry with creation of working space and it would be likely get validated if validity test was carried out.

The results showed that number of movements and number of touched objects were highly correlated with adjusted R^2=0.89 in 3D imaging. This showed that 3D imaging created more productive movements and hence contributed to more effective task performance. On the contrary, 2D imaging produced correlation coefficient of 0.891 with R^2 of 0.79, and despite the fact that this figure was still relatively high but the higher number of errors in 2D unequivocally made 2D inferior. For type of errors, pastpointing and touching wrong objects were statistically significant in 2D which showed that 2D imaging did produce more errors which should be entirely and technically avoidable in an ideal situation if 2D imaging is replaced with 3D. The error probability which was derived from the ratio of number of errors to number of movements directly showed inferiority for 2D with 10 percentage more in committing errors compared to 3D imaging.

In a nutshell, this simple and straightforward test showed independently that 3D imaging improved depth perception and contributed to enhanced task performance. Human Reliability Analysis which was a validated tool to analyze surgical task proved this beyond doubt in this experiment (Joice et al. 1998, Tang et al. 2004) As a matter of fact, this is the first study in the literature to provide scientific basis for the superior task performance in 3D. The findings of this study might be relevant and helpful in designing future software programs and algorithms, bearing in mind that 3D has impact only on volume and spatial coordinates but not in distance, area, angle and curvature.

5.3 Eye symptoms and results

For 3D imaging, several studies reported eye symptoms (Chan et al.1997 and Hanna et al. 1998). Zhou et al. 2015 found that there was no objective findings of visual fatigue in 3D imaging. However, they did reveal subjective visual findings that were significant in 3D from the symptoms score (interview). Another study on stereoscopic 3D entertainment showed that there was no clear difference between the 2D and 3D systems despite the presence of some mild changes in visual functions (eyestrain) and visually induced motion sickness. They concluded that using a stereoscopic 3D for up to 2 hours was acceptable for most of the users (Polonen M, 2013). For 2D imaging, literature review did not reveal any significant findings in visual symptoms.

Our study revealed a significant difficulty in refocusing from one distance to another in 3D imaging (p= 0.027) compared to 2D. Surprisingly for eye symptoms within the imaging, eye strain was noted to be statistically significant in 2D imaging (p = 0.022) and difficulty in refocusing from one distance to another was significant in 3D (p= 0.035). The eye strain and headache were marginally significant in 3D. These visual symptoms in 3D could be because the participants have to adapt and adjust to the 3D environment for the initial period before commencing on the task. This is also further complicated by the need of wearing special glasses for 3D. This adaptive phase gives rise to difficulty in refocusing from one distance to another. The eye strain in 2D imaging was puzzling but it may be explained by cognitive overload on the students when they encountered the components test especially the creation and measurement method. The measurement method was taxing and a student had to mentally visualize and calculate using the given reference scale to estimate the measurement of different shapes such as rectangles (for distance), squares and circles (for area), angles and volumes. This would have possibly affected cognitive capacity and led to eye strain. 3D imaging also produced eye strain and headache (p =0.061, p= 0.057) which was marginally close to significance.

Our study was also designed to analyse the effect of eye exercises in 3D imaging and to assess any significant benefit in exercising eye muscles. This is the first study that investigates the potential benefits of eye exercises to reduce the visual symptom in 3D imaging.

Eye exercise is one of the therapies for visual problems such as myopia and visual-motor disturbances. There are a variety of eye exercises reported in literature. Twice daily eye exercises are widely used among Chinese school pupils to relieve ocular fatigue and reduce myopia (Lin Zhong et al. 2013). The eye exercises for our study were chosen because they were short, simple and easy to apply.

Our results showed that eye exercises had no effect on 3D visual symptoms. There are two possible explanations for these findings. It might be that the duration of 3D surgical task in this study was not long enough to precipitate visual symptoms. The other possible explanation is that the two minutes eye exercises in this study was not long enough to be effective.

Maddox Wing device was used to measure the eye divergence during 2D and 3D imaging. None of the subjects in either group showed signs of horizontal eye deviation as measured by the Maddox Wing. However, eye exercises in the 3D group resulted in less eye deviation when compared to 3D group without eye exercises ($p = 0.05$). This indicates that eye exercises may have a beneficial impact on the movement of extraocular muscles. It may be that eye deviation is one of a number of components triggering the visual symptoms.

5.4 Limitation

There were some restrictions in this study. Firstly, the sample size of 24 students was moderate and increasing the sample size may have produced better results. Secondly, there were some students who were exposed to 3D computer games and it may have influenced their performance in 3D imaging. In retrospect, designing number of similar surrogate tests that mimic clinical laparoscopic surgery i.e. using animal models, to answer this hypothesis would may have made a difference in results. Apart from that, the spatial coordinates and component test were not long enough to cause visual symptoms and would not reflect the actual surgical practice. But, increasing the duration for this experiment was not feasible as the student may have to endure stress of longer duration and it would have been counterproductive.

CHAPTER 6

Chapter 6 Conclusion

6.0 Conclusion

This was the first study that revealed the underlying reason for the better task performance in 3D. There was no statistical difference in angle, area, distance and curvature in 2D versus 3D imaging but there was a statistical difference in volume comparisons. Apart from that, the spatial coordinates produced statistical significance results in 3D imaging and we could safely conclude that spatial coordinates was the pivotal for the enhanced 3D imaging. Human Reliability Analysis proved that spatial coordinates in 3D independently brought out few number of errors and more number of movements that were highly correlated with number of touched objects compared with 2D. Besides, the simple eye exercises had no effect in the improvement of visual symptoms in 3D.

6.1 Recommendation from the research

As this study had provided scientific basis and reason for better task performance in 3D, surgeons should openly embrace 3D laparoscopy and maximize the potential of 3D technology. Development of surgical software and algorithms need to take account of the fact that there is a significant change in volume comparisons and spatial coordinates in 3D while there are no changes in distance, area, angle and curvature.

6.2 Future direction

In future, there is a need to perform well-designed randomized controlled study (RCT) to explore the effect of eye exercises at different duration on 3D visual symptoms at clinical setting. Furthermore, we need to design a study to find out the fundamental difference between the real word 3D (open surgery) and 3D imaging in lab or clinical settings, emphasizing on physical, cognitive and surgical task changes.

CHAPTER 7

Chapter 7 Reference

7.0 Reference

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CHAPTER 8

Chapter 8 Appendices

8.0 Appendices

8.1 Participant information sheet

PARTICIPANT INFORMATION SHEET

Research Title: The influence of angle, area, volume, curvature, distance and spatial coordinates in surgical task performance in 2D and 3D laparoscopy.

INVITATION TO TAKE PART IN A RESEARCH STUDY

You are being invited to take part in a research study, which is related to laparoscopic surgery. The research will be done at Cuschieri Skills Centre, Ninewells Hospital. This research is done by Mr Gobinath Ramakrishnan, master student by research under the supervision of Mr Afshin Alijani and Mr Ian Tait.

PURPOSE OF THE RESEARCH STUDY

The study has been designed to investigate the underlying reasons for the better task performance of 2D versus 3D laparoscopic surgery. The participation in this research will help in understanding the strength or weakness of the 2D versus 3D laparoscopic surgery.

YOUR CONTRIBUTION IN THE STUDY

Upon registering your interest, you will receive an appointment to visit Cuschieri Skills Centre. The timings of your visit will be arranged at a mutually convenient time.

You will take part in a number of tests in 2D and 3D laparoscopic surgery. Before the test, you will be asked to take part in visual acuity test in both eyes and your eye divergence will be measured using a simple non-invasive test by looking through a measuring instrument. Then, you will be asked to create, compare and measure precut papers in the form of square, angle and circle. For the creation task, you will be asked to create a given distance and for the comparison task you will be asked to arrange the given distance from the smallest to the largest. And for final task, which is the measurement, you will be asked to estimate a given distance. For the spatial coordinates, you will be asked to touch suspended objects in a laparoscopic box using an instrument in 2D and 3D imaging system. Some of the students will be randomised to undergo eye exercises before the 3D imaging spatial coordinates test. The eye exercises involve three simple and quick steps to relax the extraocular muscles. The laparoscopic view of the tests will be video recorded for analysis.

TIME COMMITMENT

You will be required to attend one session of around 25 to 30min.

COST, REIMBURSEMENT AND COMPENSATION

Your participation in this study is voluntary.

RISKS

There are no known risks for you in this study.

TERMINATION OF PARTICIPATION

You may decide to stop being a part of the research study at any time without explanation and without penalty.

CONFIDENTIALITY/ANONYMITY

The data collected do not contain any personal information about you.
The data will be seen only by the researchers and will not be made available to anyone else. The video recordings will be kept until the final report is completed, after which time they will be handed over to Cuschieri Skills Centre. The results will be published in a research thesis which will be submitted to Dundee University. We have the intention to publish the data in peer reviewed journals.

FOR FURTHER INFORMATION ABOUT THIS RESEARCH STUDY

I will be glad to answer your questions about this study at any time. You may contact me at gramakrishnan@dundee.ac.uk or drop by at Cuschieri Skills Centre, Ninewells Hospital.
The University Research Ethics Committee of the University of Dundee has reviewed and approved this research study. Thank you

Mr Gobinath Ramakrishnan
Master student, Cuschieri Skills Centre, Ninewells Hospital.

8.2 Consent form

CONSENT FORM

Research Title: The influence of angle, area, volume, curvature, distance and spatial coordinates in surgical task performance in 2D vs 3D laparoscopy

I confirm that I have read and understand the Information Sheet for the above study, have had the opportunity to ask questions, and understand what I am expected to do as a volunteer.

Yes/No

I understand that my participation is voluntary and I am free to withdraw at any time, without giving any reason, without my rights being affected.

Yes/No

I do agree that the video materials recorded during the study may be used for illustration purposes in reports and any subsequent journal articles. This is on the understanding that, while every effort will be made to preserve my anonymity, this cannot be guaranteed.

Yes/No

______________________________ ________________
Participant's signature Date

____
Participant's name

______________________________ ________________
Signature of person obtaining consent Date

Mr. Gobinath Ramakrishnan

8.3 Study advertisement

Laparoscopic 2D and 3D Surgical Research

For medical students,

Want to get involved in state of the art 3D technology research?

For those who are interested, please contact Mr Gobinath R, g.ramakrishnan@dundee.ac.uk for appointment. This research is supervised by Mr Afshin Alijani PhD, FRCS(Ed), Consultant Upper GI and Bariatric Surgeon, Ninewell's Hospital.

You will be required to spend a **single session of 30minutes** at Cuschieri Skills Centre, Ninewell's Hospital.

Approved by University of Dundee Research Ethics Committee (UREC 15100)

8.4 Data record sheet

Name-

Visual acuity – LE - RE- Maddox Wing (MW)-

Visual Analogue Score (VAS) –

2D Ball Touching Test- 1min Result – Video Recorded

2D Components Test

	Create	Compare	Measure
Area	X	Sq- Cir-	Sq- Cir-
Distance	a) b) c) d)		a) b) c) d)
Curvature	X		x
Angle	a) b) c)		a) b) c) d)
Volume	a) b) c)		a) b) c)

VAS - MW –

Name- Visual acuity – LE - RE-

Maddox Wing (MW)-

Visual Analogue Score (VAS) Eye exercises – random

3D Ball Touching Test – 1min

3D Components Test

	Create	Compare	Measure
Area	x	Sq- Cir-	Sq- Cir-
Distance	a) b) c) d)		a) b) c) d)
Curvature	x		x
Angle	a) b) c)		a) b) c) d)
Volume	a) b) c)		a) b) c)

VAS-

MW-

8.5 Summary of study results

Results

From small to big

Less curvy to more curvy

	Create	Compare	Measure
Area Reference - 1.5cm	x	Sq- G,W,B,Y, R Cir- R,G,Y,B	Sq- 4cm,6cm,7cm,9cm Cir- 5cm,6cm,7cm,9cm
Distance Reference- 1.5cm	a)2cm b)3.5cm c)4.5cm d)6cm	B,Y,R,G	a)4cm b)6cm c)7cm d)9cm
Curvature	x	B,R,G,Y	x
Angle Reference – 15 degree	a)5 degree b)30 degree c)50 degree	R,G,B,W,Y	a)25 degree b)35 degree c)45 degree d)65 degree
Volume Reference- 2ml	a)3ml b)5ml c)6ml	No 8 -3ml No 1- 4ml No 0- 5ml No 5- 8ml	a)3ml b)5ml c)7ml

Colour codes: R-red, G- green, B-blue, W-white, Y-yellow.

8.6 Relevant raw data of the experiments

Generic components results

		distance cr2d	**anglecr2d**	**volumecr2d**
1	2d3d wee	-0.6,-0.5,0.2,0	0,-5,-5	-1,0,0
2	2d3d wee	1.1,1.9,1.6,1	0,-15,-5	-0.5,0,-0.5
3	2d3d wee	-0.1,-0.2,-0.6,-0.7	0,-10,-5	-1,-1,-1
4	2d3d wee	0,-1,-1.2,-2	0,-5,-5	1,0,0
5	2d3d wee	-0.6,-0.25,2.5,3	0,-18,-30	0,-1.5, -1
6	2d3d woee	-0.3,0.1,0.2,-0.1	0,-15,-30	-1.5,-1.5,-0.5
7	3d2d wee	-0.1,-0.5,-0.3,-0.5	5,-5,-20	2,5,7
8	3d2d woee	0,-1,-1.2,-2	0,-5,-5	1,0,0
9	3d2d woee	-0.2,-0.2,-0.4,-0.4	0,-20,-33	2,1,1
10	3d2d woee	0.2,0.4,0.4,-0.3	0,-15,-20	0,-1,-2
11	3d2d woee	1.1,1.9,1.6,1	0,-15,-5	-0.5,0,-0.5
12	2d3d woee	0.2,0.9,1.1,1.3	0,-18,-30	0,-1.5, -1
13	2d3d woee	-0.1,-0.1,-0.1,0.2	0,-12,-5	0,-1.5, -1
14	2d3d woee	-0.3,-0.5,-0.4,0	0,-12,-5	0,2,1
15	3d2d wee	0.1,0.6,0.7,0.5	2,-10,-13	0,-1,-0.5
16	2d3d woee	0.3,-0.1,0,-0.9	-2,-18,-32	-0.2,0,0
17	2d3d woee	0.1,-0.5,-0.2,-0.7	-2,-17,-22	0.5,1,1.5
18	3d2d woee	-0.2,-0.6,-0.5,-1.4	0,-20,-30	0,-1.5,-1.5
19	2d3d woee	-0.1,-0.3,0,0.3	2,-14-18	1.5,1,0.1
20	3d2d wee	0.2,0.5,0.1,-0.4	-2,-15,-22	-0.4,-0.5,-0.5
21	3d2dwee	-0.8,-0.2,-0.2,-0.9	4,-14,-15	0,0,0
22	3d2dwee	0.2,-0.1,0.8,0.6	4,-18,-35	-1.5,1,1
23	3d2d wee	0.1,0.6,0.7,0.5	2,-10,-13	0,-1,-0.5
24	3d2d wee	-0.2,-0.6,-0.5,-1.4	0,-20,-30	0,-1.5,-1.5

sq mr2d	**cir mr2d**	**distance mr2d**	**angle mr2d**	**volume mr2d**
's,0,0,0,-1	c,-0.5,0.5,0,-0.5	0,0,0,-0.5	0,-5,-10,-15	1,1,0
's,0,1,0.5,3	c,1,2,3,6	-0.5,0.5,0.5,3	5,15,25,15	-1,-1.5,-2
's,1,0,0,1	c,1,2,0,-1	1,0,0,1	-5,-5,0,-5	0,1,1
's,0.5,1.5,1,1	c,1,1.5,2,1	0.5,0,2,1	-5,-5,-5,-5	0,-0.5,-1
s,0,-1,0,1	c,-0.5,0.5,2,3	-0.5,0.5,2,3	-5,-5,-5,-5	0.5,-0.5,-1
s,0.5, 1.5,0.5,-1	c,0,1,0.5,1	0,0,-0.5,0	-5,-5,-5,-10	0,0,-1
s,0,1,2,3	c,1,3,3.5,3	1,1.5,0.5,1.5	-5,-5,0,-5	0,-1,-1.5
s,-0.5,-0.5,-0.5,-1	c,-1.5,-0.5,-0.5,-1	0.5,0,2,1	-5,-5,-5,-5	0,-0.5,-1
s,0.5,1.5,-1,-1.5	c,1,1.5,-2,3	1,1.5,0.5,2	-5,-5,0,-5	-1,-2,-2.5
s,0,1,0.5,1.5	c,-1,3,2,2	1,2,2,2	5,5,5,15	0,-1,-2

's,0,1,0.5,3	c,1,2,3,6	-0.5,0.5,0.5,3	5,15,25,15	-1,-1.5,-2
s,0,-1,0,1	c,-0.5,0.5,2,3	-0.5,0.5,2,3	-5,-5,-5,-5	0,0,-1
s,0.5,0,2,7	c,2.5,4,5,9	0.5,0,0.5,9	-5,-5,-5,10	1,3,3
s,0.5,3,-1,-1.5	c,1,1.5,2,0	0.5,-1,-1,-1.5	5,5,5,0	-0.5,-2.5,-4
s,0.5,0,0.5,0	c,-0.5,0,0.5,-1.5	0.5,0,0.5,-1.5	0,0,15,15	0,-1.5,-2
s,1,3,0.5,4.5	c,1,3,3,6	0.5,1.5,0.5,5	-5,-5,0,-5	-0.5,-1.5,-3
s,0,0,0.5,0	c,0,0,0.5,0	0.5,0,0.5,1.5	-5,-5,-10,-25	-1,-2,-3
s,2,0.5,0.5,0	c,-0.5,0,0.5,0	0.5,0,0.5,0.5	5,10,5,-5	-0.5,0,0
s,3.5,3,1,0	c,-1,-1,0,0	0.5,-0.5,0,0	-5,5,0,-5	-1.5,-2,-3.5
s,0,0,0.5,0	c,0,0,0,0	0,-0.5,-1,0	0,0,0,15	-1,-1,-1
s,0.5,1,-3,1.5	c,1,3,-5,2	0.5,1,1,2	-5,-5,-5,5	0,-1,-2
s,-1.5,-2.5,-1,-2	c,-2,-2,-1,-1	-1.5,-1.5,-2,-2	5,15,25,20	0,-1.5,-1.5
s,0.5,0,0.5,0	c,-0.5,0,0.5,-1.5	0.5,0,0.5,-1.5	0,0,15,15	0,-1.5,-2
s,2,0.5,0.5,0	c,-0.5,0,0.5,0	0.5,0,0.5,0.5	5,10,5,-5	-0.5,0,0

distance cr3d	**angle cr3d**	**volume cr3d**	**area cp3d**	**distance cp3d**
-0.25,0.25,1.75,1	3,-5,5	-0.5,0,0	s,3/5,c,2/4	1/4
1,0.4,0.6,-0.4	0,-15,-20	-0.2,0,0	s,5/5,c,4/4	1/4
-0.2,-0.8,-0.9,-1.7	0,0,-2	-1,-1-1	s,3/5,c,4/4	2/4
-0.5,-1.1,-0.4,-1.1	0,-5,10	-0.8,-0.5,0	s,5/5,c,4/4	2/4
0.4,1.3,2.5,-2.6	2,-10,-25	-0.9,-1.4,0.1	s,2/5,c,4/4	0/4
0,0.2,0.4,0.1	0,-20,-32	0,-0.5,0	s,2/5, c, 4/4	0/4
0.1, -0.2,-0.9,-2	5,-10,-10	0.2,1,1	s,1/5,c,2/4	0/4
-0.5,-1.1,-0.4,-1.1	0,-5,10	0,0,0.5	s,2/5,c,4/4	0/4
-0.4,-0.3,-0.3,0	0,-20,-35	-0.2,-1,-0.5	s,2/5,c,2/4	2/4
0,0.2,0.4,0.1	0, -17-20	-0.2,-1,-0.5	s,3/5,c,4/4	0/4
0,0.25,-0.4,0.7	0,-15,-20	-0.2,0,0	s,2/5,c,4/4	0/4
0.5,0.8,0.4,1.3	2,-10,-25	-0.9,-1.4,0.1	s,2/5.c,4/4	1/4
0,0.1,-0.2,0	-1,-10,-10	0.5,-1,-1	s,2/5,c,4/4	0/4
-0.3,-0.7,-0.6,0	3,0,-10	0.1,0.1,1	s,3/5,c,4/4	1/4
-0.4,0.3,-0.2,0.2	2,-10,-15	0.2,-0.8,-0.4	s,5/5,c,2/4	2/4
0,-0.7,-1.2,-1.5	0,-19,-20	0,-1.5,-1	s,2/5,c,4/4	2/4
0.5,0.6,1.0, 1	0,-15,-22	0,1,0	s,3/5,c,4/4	2/4
-0.4,-1.3,-1.1,-1.2	1,-15,-25	0,-0.9,-1	s,3/5,c,4/4	2/4
0,-0.9,-1.7,-0.5	-1,-17,-20	0,-0.9,-1	s,2/5,c,4/4	1/4
0,0.3,0.4,0.5	-2,-16,-20	0,-0.5,-0.8	s,2/5,c,4/4	0/4

-0.5,-0.5,-0.4,-0.9	3,-10,-20	0.5,1,0	s,3/5,c,2/4	1/4
0,-0.4,0.4,1.2	3,-15,-20	-1,0,1	s,3/5,c,2/4	2/4
-0.4,0.3,-0.2,0.2	2,-10,-15	0.2,-0.8,-0.4	s,5/5,c,2/4	2/4
-0.4,-1.3,-1.1,-1.2	1,-15,-25	0,-0.9,-1	s,3/5,c,4/4	2/4

volume cp2d	**volume cp2d**	**sq mr3d**
4/4	4/4	's,0,0,0,-1
2/4	2/4	's,-0.5,2,3,4
2/4	2/4	's,0.5,0,0,-1
4/4	4/4	's,2,4,2,3
2/4	2/4	s,0,-1,0.5,1
2/4	2/4	s,0.5,0,0.5,0.5
4/4	4/4	s,-0.5,1,2,1.5
4/4	4/4	s,0.5,0,-1,-1
2/4	2/4	s,0,2,2,1.5
2/4	2/4	s,0.5,1,0.5,0
2/4	2/4	's,2,4,2,3
4/4	4/4	s,0,-1,0.5,1
4/4	4/4	s,1.5,2,3,6
4/4	4/4	s,1,1.5,0,-1.5
4/4	4/4	s,0.5,1.5,0.5,0
4/4	4/4	s,0.5,3,1,4
4/4	4/4	s,-1,-1.5,-1,0
4/4	4/4	s,2,1.5,0.5,0.5
2/4	2/4	s,2,2,1.5,0.5
4/4	4/4	s,1,2,2,2
4/4	4/4	s,1,1,2,1.5
4/4	4/4	s,-1.5,-2.5,-2.5,-3.5
4/4	4/4	s,0.5,1.5,0.5,0
4/4	4/4	s,2,1.5,0.5,0.5

cir mr 3d	**distance mr3d**	**angle mr3d**	**volume mr3d**
c,-0.5,0.5,0,-0.5	0,0,0,-0.5	0,-5,-10,-15	1,1,0
c,2,5,5,6	0,2.5,2.5,4	-5,-5,5,15	0,-1,-1
c,-0.5,0,0,-1	0.5,1,0,-1	-5,-5,-5,5	1,-1,1
c,-1,1.5,2,1	2,1.5,2,1	-5,-5,-5,-5	0,-1,-1
c,-1,-1,2,3	0.-1,1,3	0,0,0,-10	0,-1,-2
c,0,1.5,2,1.5	0,0.5,1,2	5,10,5,10	1,0,0
c,1,3,3.5,3	1,1.5,2,3	-5,-5,0,-5	0,-1,-2
c,-1,1,-1,-1	0.5,-1,-1,1	-5,10,15,15	-1.2,-2.5,-4
c,0,3,-2,2.5	-0.5,1,0,-1.5	0,-5,0,-5	1,1,0
c,4,4,2.5,0	0,0,0.5,0	-5,-5,0,15	1,1,0

c,-1,1.5,2,1	2,1.5,2,1	-5,-5,-5,-5	0,-1,-1
c,-1,-1,2,3	0,-1,1,3	0,0,0,-10	0,-1,-2
c,1,1,2,3	0,0.5,1.5,1	0,-5,-10,5	0.5,-1,1
c,1,1.5,2,0	0.5,0,-0.5,-1	-5,0,5,10	-0.9,-2.5,-2.5
c,-0.5,1.5,0.5,0	0.5,0,0.5,0	5,10,15,15	-1,-1,-2
c,4,6,5,6	-0.5,1.5,0.5,3	-5,-5,0,-5	0,1,1
c,-2,-1.5,-1,0	-1,-1.5,-1,0	-5,-5,0,-5	0,0,-1
c,2,2.5,0.5,0.5	2,1.5,1.5,0	5,10,10,0	0.5,1,0
c,1,2,1,0.5	2,2.5,1,1	-5,-5,-5,-15	0,-1,-2.5
c,2.5,2,2,2	1,3,1,2	-5,0,5,15	0,0,-1
c,3,8,2,3	1,1.5,0,1.5	-5,0,0,-5	0,0,-1
c,-2,-2,-2,-3	-2,-2,-3,-4.5	-5,5,15,15	0,-1,-2
c,-0.5,1.5,0.5,0	0.5,0,0.5,0	5,10,15,15	-1,-1,-2
c,2,2.5,0.5,0.5	2,1.5,1.5,0	5,10,10,0	0.5,1,0

Human reliability analysis - **Spatial coordinates test**

2dpp	**2dnr**	**2dtwo**	**2dnoe**	**2dnom**	**2dnoo**	**3dpp**	**3dnr**
1	0	2	3	11	7	2	0
0	0	0	0	14	14	0	0
0	0	2	2	8	8	0	0
0	0	1	1	13	11	0	0
0	0	2	2	17	15	0	0
2	0	1	3	14	10	0	0
1	0	1	2	14	14	0	0
0	0	0	0	14	14	1	0
1	0	1	2	13	12	1	0
2	0	2	4	18	16	1	0
3	1	1	5	21	16	1	0
0	0	0	0	15	15	0	0
1	0	2	3	14	12	0	0
1	0	2	3	17	14	0	0
1	0	1	2	12	10	0	0
2	0	2	4	8	6	0	0
2	0	1	3	13	11	0	0
1	0	2	3	17	14	0	0
1	0	0	1	14	13	0	0
2	0	4	6	18	16	1	0
2	0	2	4	13	10	1	0
2	0	3	5	15	12	1	0
1	0	1	2	12	10	0	0
1	0	2	3	17	14	0	0
			63	342			

3dtwo	3dnoe	3dnom	3dnoo
1	3	14	13
0	0	20	18
2	2	10	10
0	0	16	16
1	1	21	20
1	1	17	17
1	1	13	12
2	3	18	16
0	1	14	14
2	3	15	12
1	2	17	16
0	0	16	16
2	2	19	18
2	2	22	18
1	1	12	11
0	0	13	13
0	0	21	21
2	2	22	18
0	0	26	26
1	2	18	15
1	2	13	12
2	3	12	10
1	1	12	11
2	2	22	18
	34	403	